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ORIGINAL

Degradation of Nuclear Plant Temperature Sensors

Prepared by H. M. Hashemian, K. M. Peterson, T. W. Kerlin,
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Analysis and Measurement Services Corporation

Prepared for
U.S. Nuclear Regulatory
Commission

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ABSTRACT

A program was established and initial tests were performed to evaluate long term performance of resistance temperature detectors (RTDs) of the type used in U.S. nuclear power plants. The effort addressed the effect of aging on RTD calibration accuracy and response time. This Phase I effort included exposure of thirteen nuclear safety system grade RTD elements to simulated LWR temperatures. Full calibrations were performed initially and monthly, sensors were monitored and cross checked continuously during exposure, and response time tests were performed before and after exposure. Short term calibration drifts of as much as 1.8°F (1°C) were observed. Response times were essentially unaffected by this testing.

This program shows that there is a sound reason for concern about the accuracy of temperature measurements in nuclear power plants. These limited tests should be expanded in a Phase II program to involve more sensors and longer exposures to simulated LWR conditions in order to obtain statistically significant data. This data is needed to establish meaningful testing or replacement intervals for safety system RTDs. An important corollary benefit from this expanded program will be a better definition of achievable accuracies in RTD calibration.

This report concludes a six-month Phase I project performed for the Nuclear Regulatory Commission under the SBIR program.

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1. INTRODUCTION

1.1 Project Objectives

The objectives of this Phase I research effort were:

1. Identify and evaluate static and dynamic performance requirements on resistance temperature detectors (RTDs) of the type used for safety related temperature measurements in U.S. nuclear power plants.

2. Develop a test program to evaluate degradation in calibration and response time of RTDs as they age in a nuclear power plant.

3. Initiate laboratory testing according to the program developed under objective 2.

4. Evaluate performance limits and testing intervals for RTD requalification or replacement.

5. Evaluate available methods for testing the performance of RTDs as installed in an operating plant (in-situ testing).

1.2 Project Importance

RTDs are essential components of many LWR safety systems. Their indications must be accurate and timely in order for the safety system to operate properly. This can be achieved only by assuring initial, as-installed accuracy and response times and by determining possible drift rates in both of these quantities. The drift rate information is essential for establishing proper recalibration or replacement schedules.

Performance requirements on measurement accuracy and response time of nuclear plant RTDs both approach technically achievable limits. Therefore, it is essential to optimize sensor design, selection and use and to determine reliable information on achievable performance limits.

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1.3 Work Completed in this Project

The objectives stated in the Phase I proposal were met in this project. Furthermore, the laboratory testing to evaluate sensor degradation progressed significantly further than anticipated. The specific accomplishments are:

1. Identification of performance requirements. Response time and accuracy requirements were identified for eight nuclear power plants. The results are shown in Section 3 of this report.

2. Test Program Development. A test program was developed and facilities were assembled for assessing changes in sensor accuracy when exposed to simulated thermal environments in nuclear power plants. This program included sensor calibration, thermal aging in a simulated reactor environment, drift monitoring as sensors aged, periodic insulation resistance measurements, and response time testing before and after aging.

3. Initial Laboratory Testing. Thirteen typical nuclear grade RTD elements were exposed to 637°F (336°C) air in a furnace for three months. Readings were made on each sensor every five minutes. Each sensor was removed monthly for a full calibration. Response time testing was performed initially and after the three-month aging period. Test results are presented in Section 5.

4. Performance Limits. The three month exposure of thirteen sensors to drift testing at typical LWR conditions provides a small initial entry to the data base needed for meaningful statistical assessment of performance. Results are presented in Section 5.

5. In-Situ Testing Methods. Possible methods for in-situ performance testing of RTDs were reviewed. The investigation is reported in Section 6.

6. Performance of Platinum Resistance Thermometers in Nuclear Power Plants. To provide a vehicle for exchanging information among members of the AMS research team and for communicating with other interested parties, a review paper was prepared. It is included as Appendix A of this report.

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2. STATIC ACCURACY AND DYNAMIC RESPONSE

2.1 Static Accuracy

A nuclear plant RTD is generally a stainless steel sheathed sensor as shown schematically in Figure 2.1. In some plants the sensors are installed in thermowells and in others they are inserted into primary loop water flowing through a by-pass manifold. The resistance element is platinum doped with a trace of rhodium so as to give a temperature dependent resistivity which can be achieved reproducibly and economically. The platinum may be a wire or a film mounted on an insulating support structure. Special effort is spent to achieve ruggedness yet adequate freedom of motion of the platinum relative to the support structure. This freedom of motion is to avoid strain effects caused by differential thermal expansion which could interfere with temperature measurements.

The resistance at a selected, reference temperature is adjusted by selecting the cross sectional area and length of the platinum. Ice point resistances are used as references and typical values for nuclear plant RTDs are 100 ohms and 200 ohms. The temperature (T) vs. resistance (R) relation is usually represented as a second order polynomial. One form is

$$R = a + bT + cT^2 \qquad (2.1)$$

The sensitivity is approximately 0.385% resistance/°C.

Sensors are built in three wire and four wire configurations. These permit compensation for the effects of lead wire resistance (See Appendix A).

Calibration of an RTD involves measuring the resistance at three or more known temperatures. The R vs T values are then fit to an equation of the form of Equation 2.1. The equation with the fitted coefficients is then used to generate calibration tables (R vs T at any temperature of interest). The calibration data are then used to tune the RTD transmitters which converts the resistance to an equivalent voltage or current. The accuracy of the indicated temperature depends on the accuracy of the RTD calibration and the RTD drift rate which are addressed in this project.

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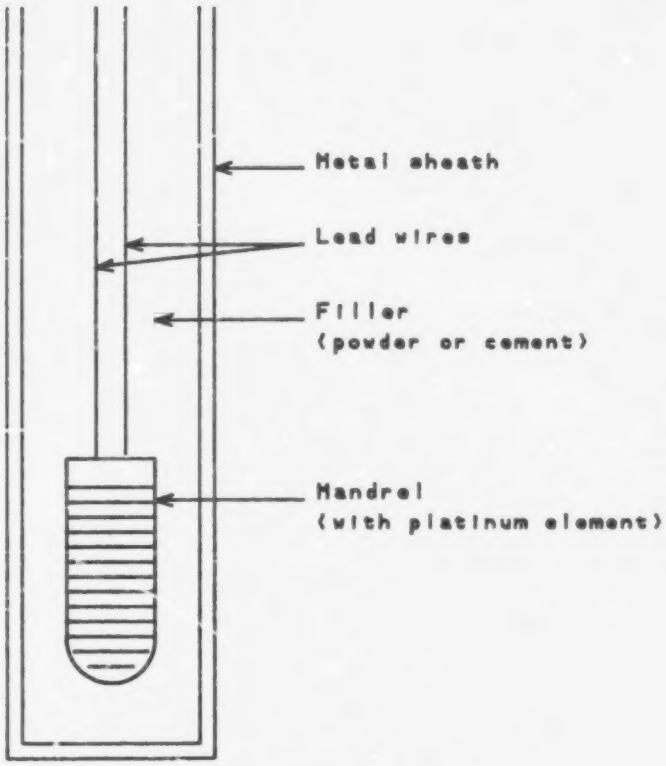

Figure 2.1. Simplified schematic of a typical RTD.

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2.2 Dynamic Response

Because of heat diffusion effects, temperature sensors always lag behind changing process temperatures. A typical RTD response to a step change in temperature is shown in Figure 2.2. An index used to characterize sensor response is the time constant, defined as the time required for the response to reach 63.2 percent of the total change following a step in monitored temperature.

Sensor time constants increase with increased heat capacity of sensor constituents and with increased thermal resistance between the sensing element and the monitored fluid.

Responses of sensors used in thermowells are strongly affected by the fit between the sensor and the thermowell because of the large thermal resistance caused by small gaps in the heat transfer path.

Sensor time constants for RTDs in nuclear power plants generally range from 0.1 sec to over 10 sec. The fast sensors are special, direct immersion sensors which are designed to have a very low heat capacity and a very low thermal resistance. Typical time constants for sensors in thermowells are 5 sec to 10 sec. Time constants as large as 40 sec have been measured in cases where the sensor/thermowell fit was poor.

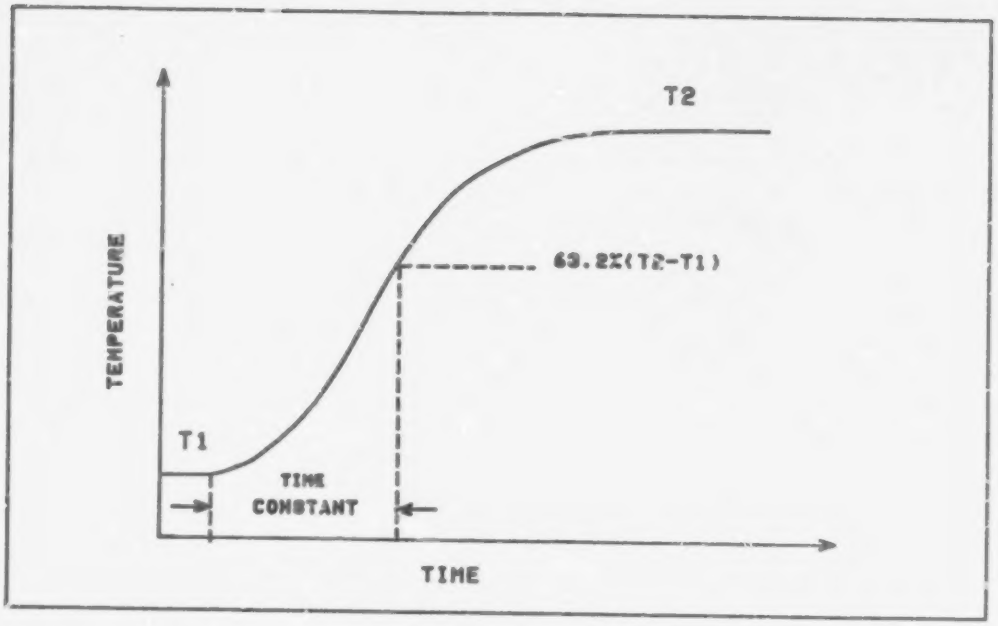

Figure 2.2. Typical response of an RTD to a step change in temperature.

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3. RTD PERFORMANCE REQUIREMENTS IN NUCLEAR POWER PLANTS

Eight utilities were contacted to determine accuracy and response time requirements for safety system RTDs. The results are shown in Table 3.1. This limited survey indicated accuracy requirements between 0.02°F (0.01°C) and 2.5°F (1.4°C) and time constant requirements between 4 sec and 15 sec. This survey was very informal. Plant instrumentation technicians or engineers provided their best knowledge of sensor requirements from purchasing specifications or technical specifications. The information was obtained in telephone interviews. The lesson from this survey is the order of magnitude of performance requirements and the wide range of requirements at different plants.

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TABLE 3.1

Typical RTD Performance Requirements in Various Operating Nuclear Power Plants

Sensor Type	Accuracy & Drift Requirements	Response Time Requirement
In Thermowell	±2.5°F total channel accuracy (including drift)	13 sec (hot leg) 8 sec (cold leg)
In Thermowell	0.31°F RTD calibration accuracy 0 to 750°F 1.09°F (total channel accuracy including 22 month drift)	6 sec
In Thermowell	±1.5°F for sensor cross calibration	8 sec
Direct Immersion	±0.5°F calibration accuracy ±1.2°F for sensor cross calibration ±0.7°F drift/18 months	4 sec for RTD, rack and breaker (Rack & Breaker 0.1 sec each)
Direct Immersion	±0.2°F calibration accuracy ±0.5°F drift for life of plant	4 sec for total channel
In Thermowell	±0.4% (from 520-620°F) calibration accuracy (40 year repeatability: 0.05% of initial calibration at 32°F)	4 sec
In Thermowell	1% of the reading	15 sec
In Thermowell	±0.02°F calibration accuracy Repeatability ±0.2°F	4 sec

4. LABORATORY TESTING METHODS

4.1 Static Performance Testing

The static performance testing program required automation of calibration capability and construction of test facilities for providing simulated LWR conditions for drift testing.

The calibration approach developed is a balance between accuracy, ease and speed of calibration, and cost. The system includes:

1. A Hewlett-Packard Model 3457A precision digital multimeter for measuring RTD resistance to be converted to equivalent temperature.

2. An ice bath and an oil bath with agitator and temperature controller. The sensors were installed in a copper block in the oil bath to improve temperature stability.

3. Precision reference RTDs for measuring the bath temperature.

4. A rotary switch box for switching between reference RTDs and the RTDs under calibration.

The calibration uses the comparison method which involves measurement of the bath temperature (with a precision reference RTD) and the resistance of the RTD being calibrated. The sensor being calibrated was installed in the copper block adjacent to the precision RTD. After the two sensors reached thermal equilibrium, resistance measurements were made on both sensors. The reference sensor's calibration was used to obtain the bath temperature. A picture of the calibration set up is given in Figure 4.1.

An ATS Model 3210 three-zone tube furnace was purchased and adapted to provide a simulated LWR thermal environment for aging tests. The furnace was drilled to hold 15 sensors. A temperature controller was installed to control the furnace temperature. The temperature aging of the RTDs was done at about 637°F (336°C).

The sensors were all connected to a Hewlett-Packard Model 3488A switch/control unit. The set-up is shown in Figure 4.2. Each sensor was monitored every five minutes to detect sudden failures and to collect data to check for any gross drift during the aging process. The measurements were fed

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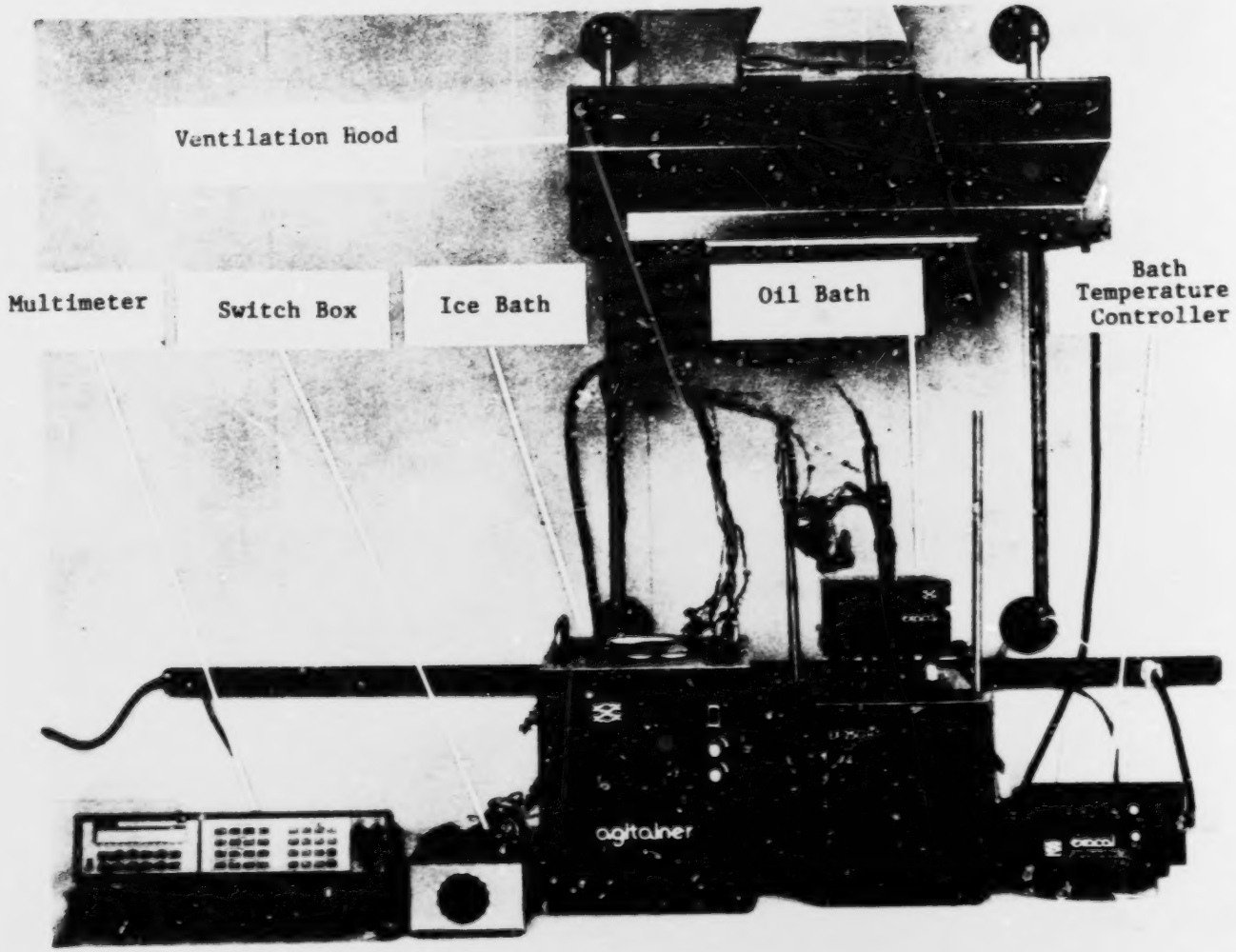

Figure 4.1. RTD calibration system.

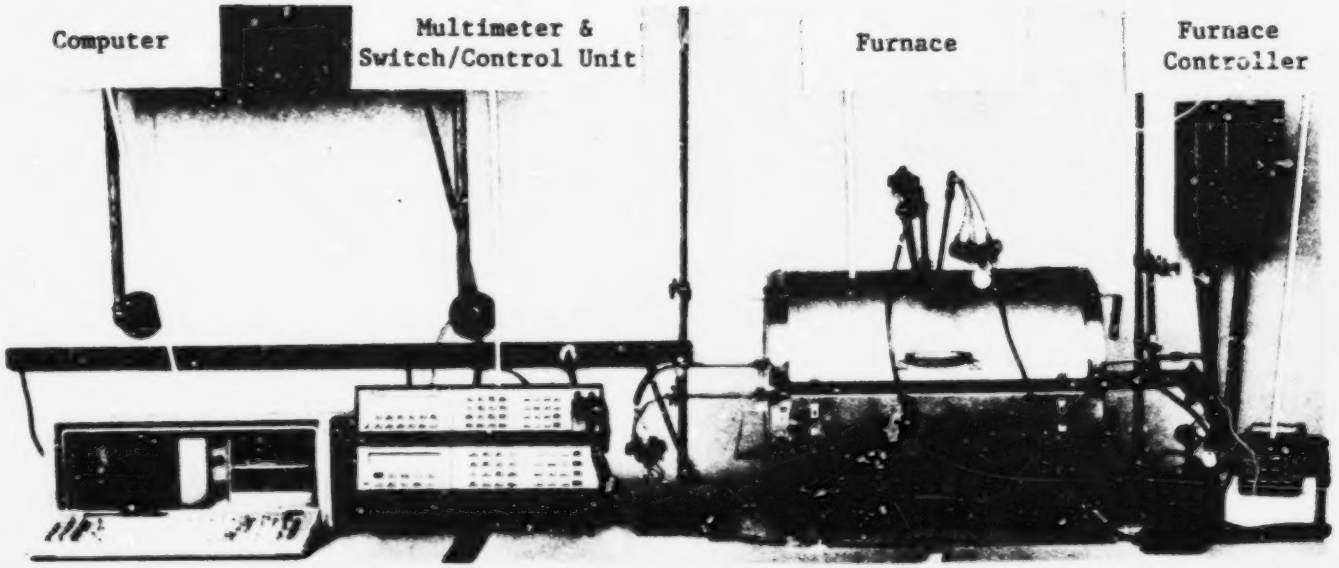

Figure 4.2. RTD drift testing system.

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to an IBM computer where the data are stored and processed. The processing involved calculating average readings from all sensors and deviations from the average value. Software was developed to permit user friendly operation of the data collection, data processing and hard copy results preparation.

Computer software previously developed at AMS was used to fit the calibration data to the Callendar equation. The Callendar equation is discussed in Appendix A and is repeated below:

$$\frac{R}{R_o} = 1 + \alpha \left[T - \delta \left(\frac{T}{100} - 1\right)\left(\frac{T}{100}\right) \right]$$

where

$R(T)$ = PRT resistance at temperature, T

R_0, α, δ = fitting coefficients

This form of the fitting equation is used for temperatures above 32°F (0°C). After the fit is complete, the computer program may be used to generate a calibration table (R vs T).

Sensors were removed from the furnace on a monthly schedule and calibrations were performed. The monthly calibration results for each RTD were compared to determine if temperature aging had caused calibration changes. A computer program was written to perform the comparison and plot the difference at all temperatures within the calibration range. Figures 4.3 and 4.4 show a sample of two RTD comparison plots obtained in the program.

4.2 Dynamic Performance Testing

The dynamic performance testing was accomplished using the plunge test method. The steps are as follows:

1. Insert the sensor into a stream of heated air until it reaches thermal equilibrium.
2. Rapidly insert the sensor into a stream of water flowing at three feet per second.
3. Monitor the sensor signal on a strip chart recorder and determine the time constant by identifying the time required to reach 63.2 percent of the total change.

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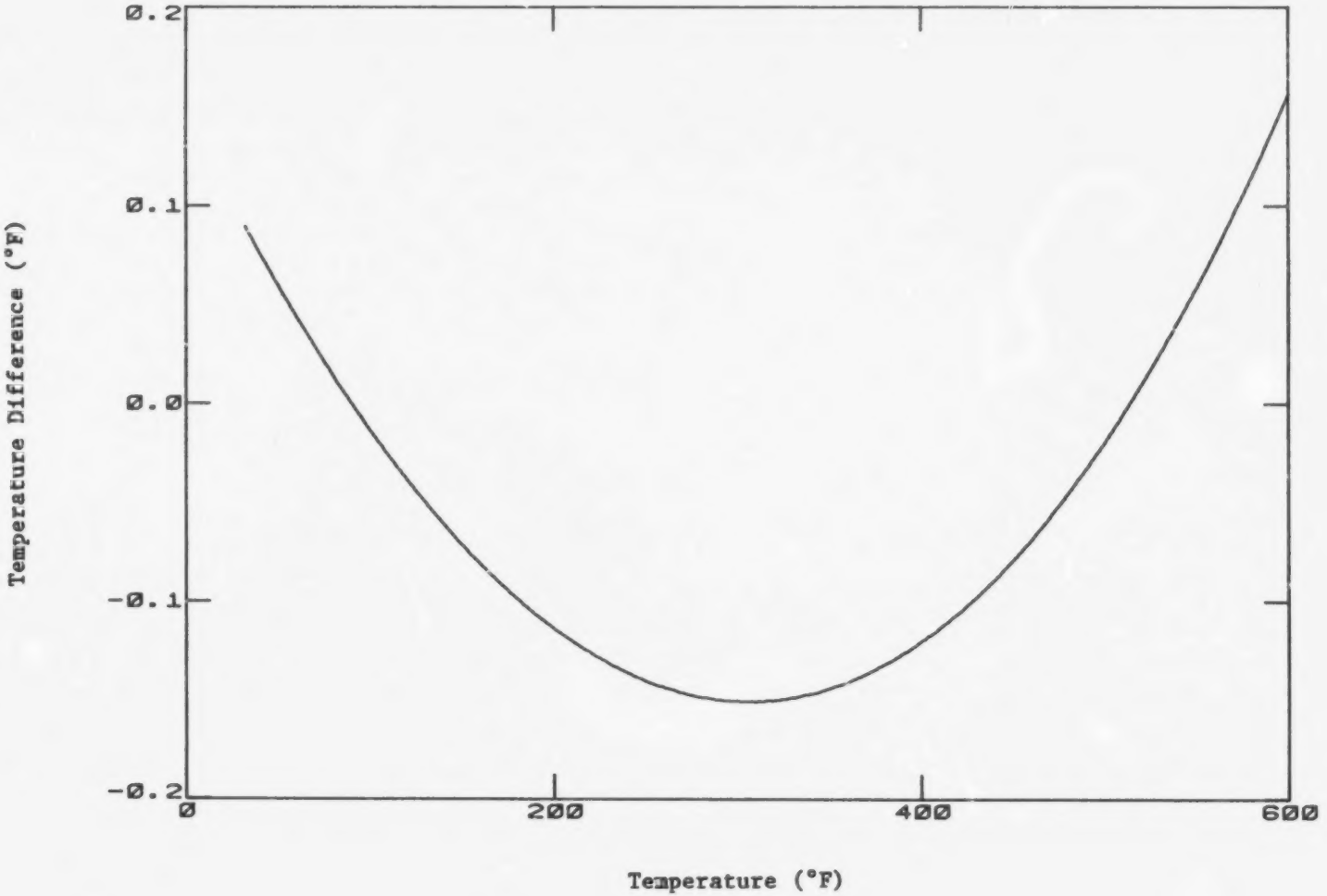

Figure 4.3. RTD calibration shift as a function of temperature.

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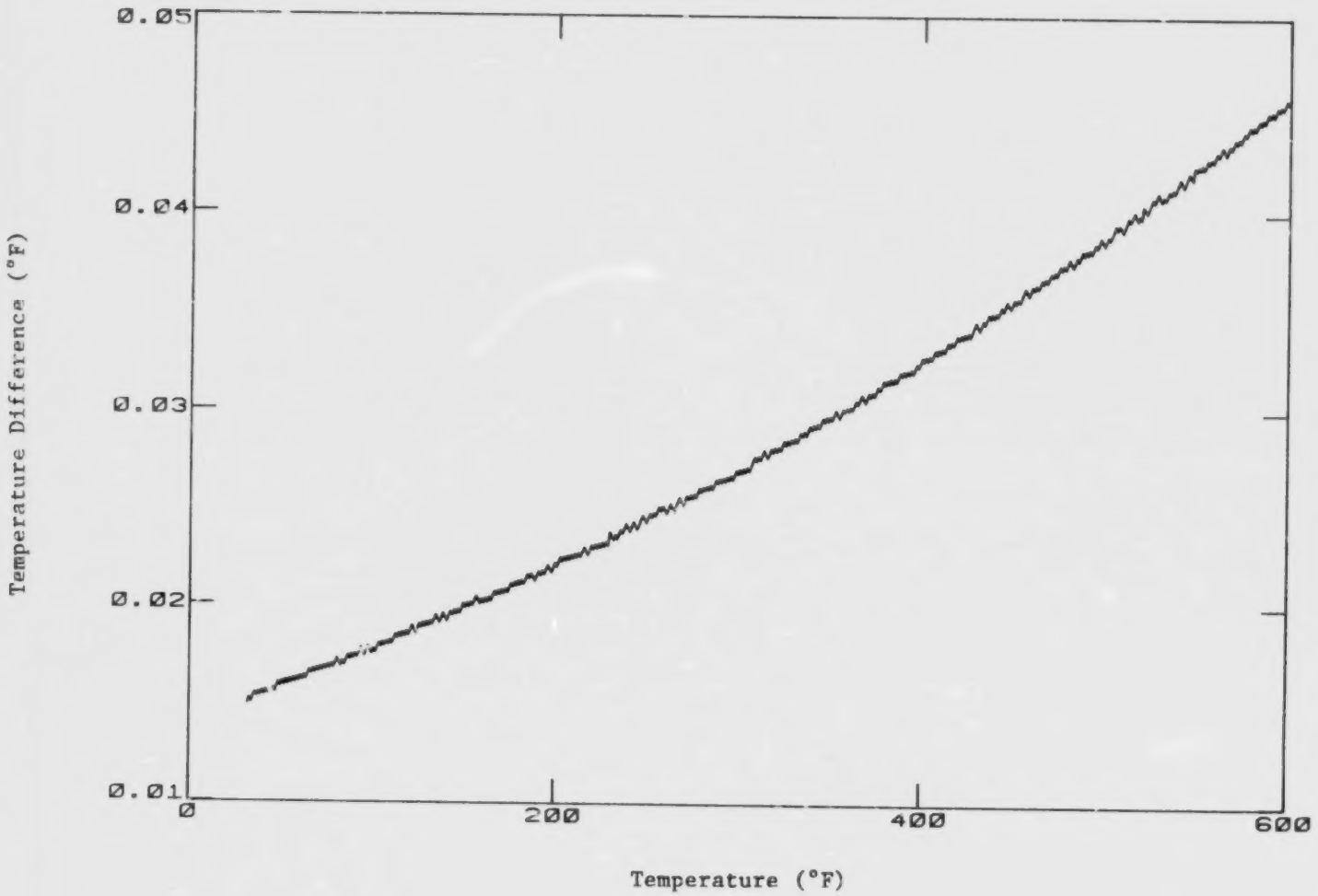

Figure 4.4. RTD calibration shift as a function of temperature.

5. LABORATORY TEST RESULTS

5.1 Description of the Sensors

Ten nuclear grade RTDs including three dual element sensors were tested in this study. A listing of these RTDs representing a total of thirteen elements is given in Table 5.1. A tag number was assigned to each RTD for identification during this project. These RTDs include at least one from each of the manufacturers of nuclear qualified RTDs. They were selected from those available at AMS and a few which were provided by interested utilities and manufacturers. This included both new and used RTDs. As such, they were a non-ideal set of test sensors because their past histories are unknown. Nevertheless, they are suitable for the testing program initiation implemented in this work.

5.2 Static Tests

The tests provided two types of data: time histories of deviations from measured average temperatures for each sensor and changes in sensor calibration at each monthly test.

Figure 5.1 shows the time history for one of the RTDs while in the furnace for approximately one month. It was obtained by subtracting the RTD indication from the average furnace temperature. The mean of the difference has been removed to account for spatial temperature variations in the furnace. The time history indicates that the RTD closely followed the average furnace temperature (within $\pm$0.1°F) and was therefore stable during the period. Figure 5.2 shows a time history plot with indication of drift during the same period. The average furnace temperature for this period is shown in Figure 5.3. Time history plots were generated for all the RTDs in this program and the results were compared with those of the monthly calibrations. It was concluded that the time history plots are useful for tracking gross calibration shifts but accurate measurements require the full calibration as was performed monthly in this program.

Results of monthly calibration tests are shown in Figures 5.4 through 5.6. These figures show deviations from the initial calibration at temperatures of 32°F, 200°F, 400°F and 600°F. The horizontal axis gives the RTD tag number and the vertical axis gives the temperature drift at four different temperatures. A precision reference RTD was also included in the program and was calibrated every month along with the other RTDs to provide a measure of our calibration repeatability. The results for this RTD is plotted as CTRL. This RTD was not exposed to temperature aging in the furnace.

The data plotted in Figure 5.6 through 5.4 were obtained by the following procedure:

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TABLE 5.1

Listing of RTDs Tested

Item	Tag #	Description
1	01	Single Element Direct Immersion
2	03	Single Element Well Type
3	04A	Dual Element Well Type. Element 1
4	04B	Dual Element Well Type. Element 2
5	5A	Dual Element Well Type. Element 1
6	5B	Dual Element Well Type. Element 2
7	6A	Dual Element Well Type. Element 1
8	6B	Dual Element Well Type. Element 2
9	07	Single Element Well Type
10	08	Single Element Well Type
11	09A	Dual Element Well Type. Element 1
12	09B	Dual Element Well Type. Element 2
13	10	Single Element, Direct Immersion

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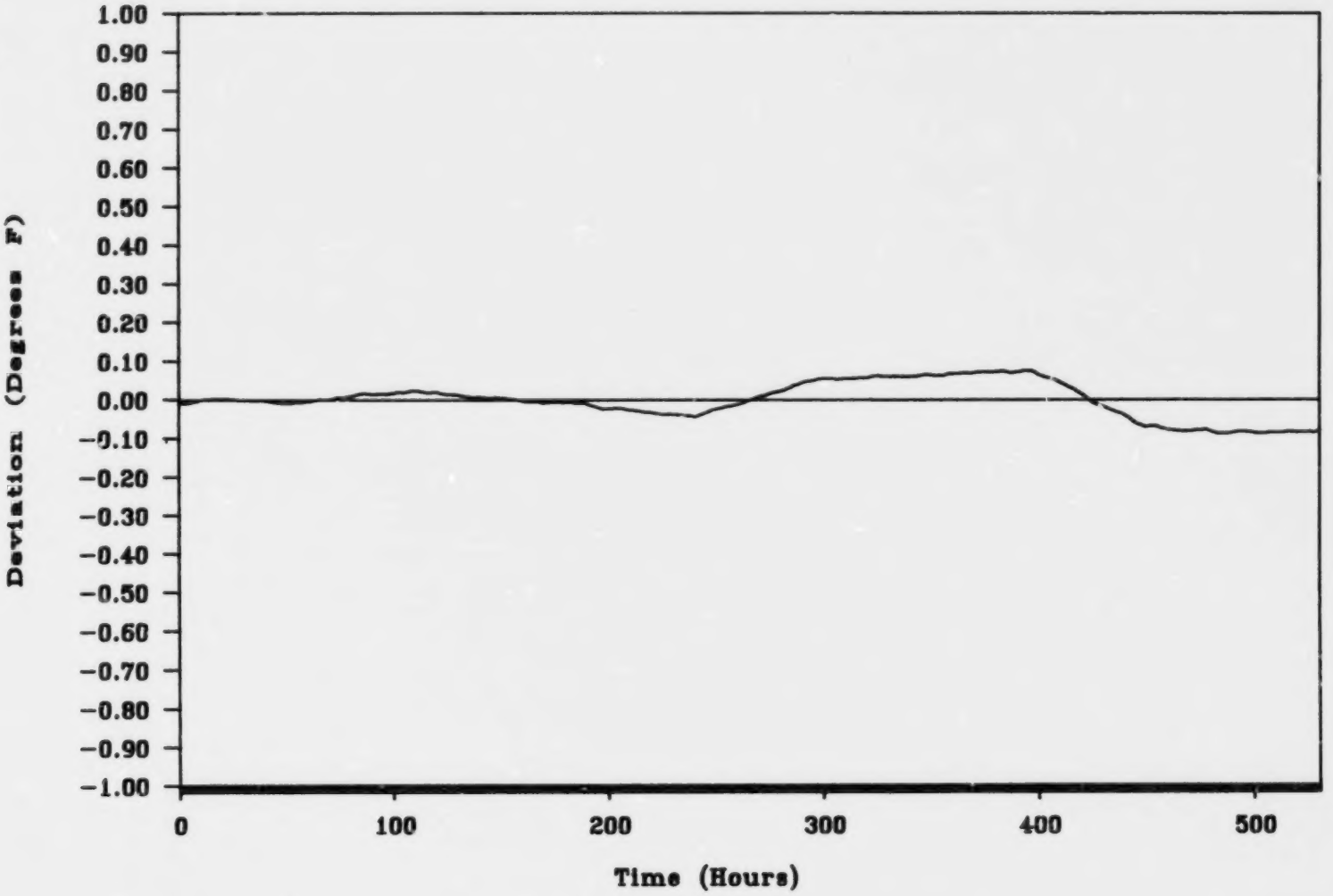

Figure 5.1. Time history for a stable RTD.

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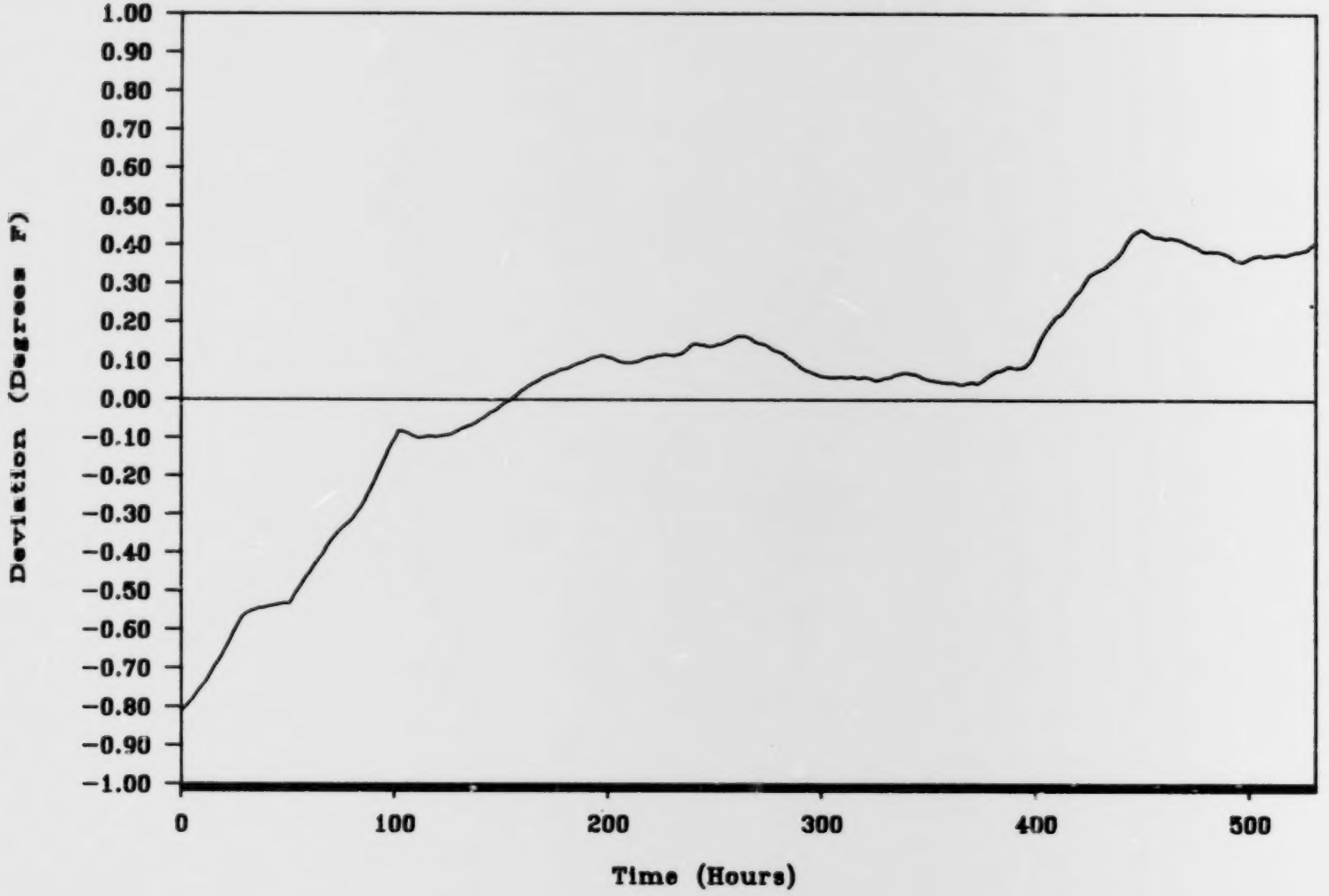

Figure 5.2. Time history for a drifting RTD.

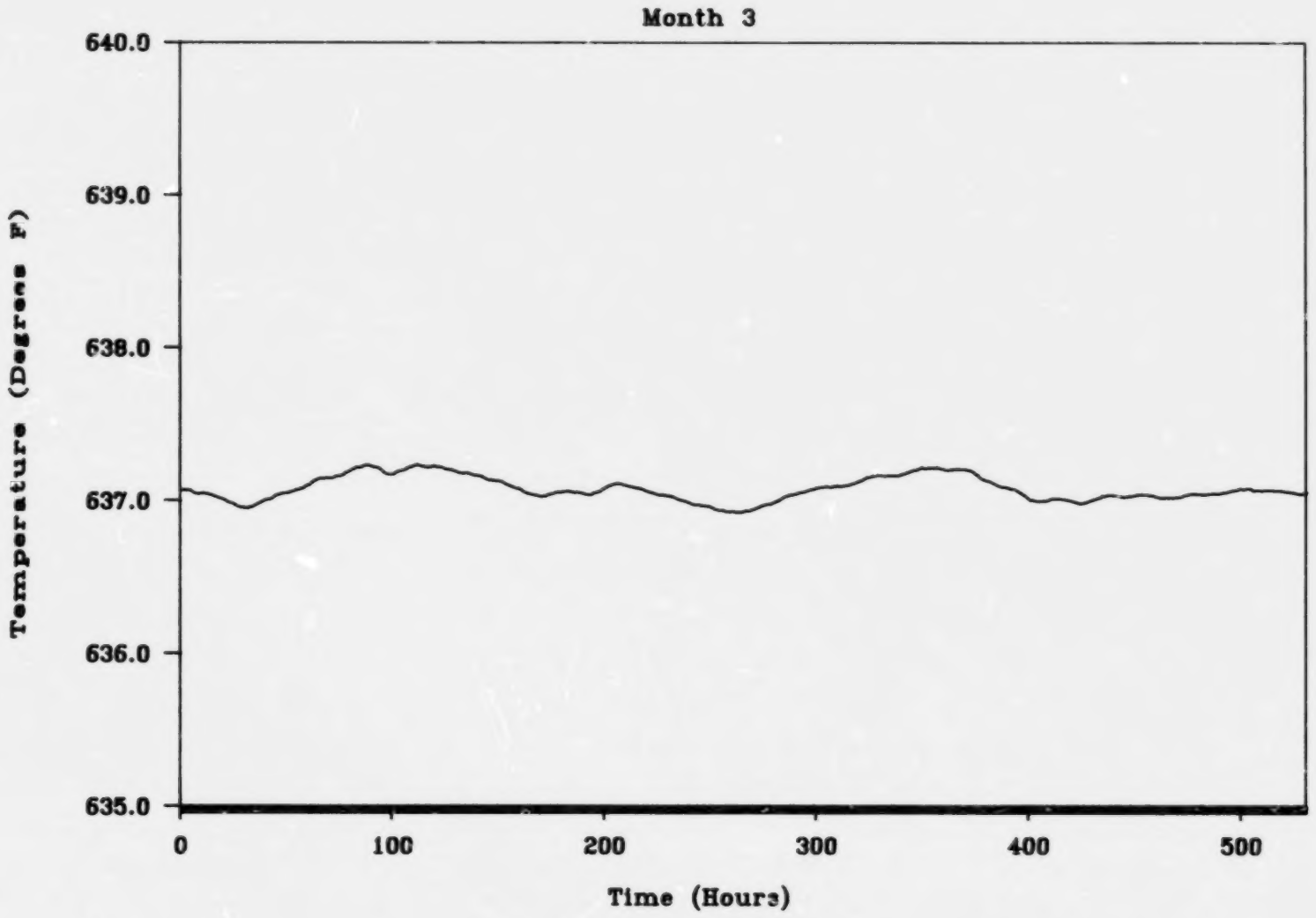

Figure 5.3. Average temperature in the furnace.

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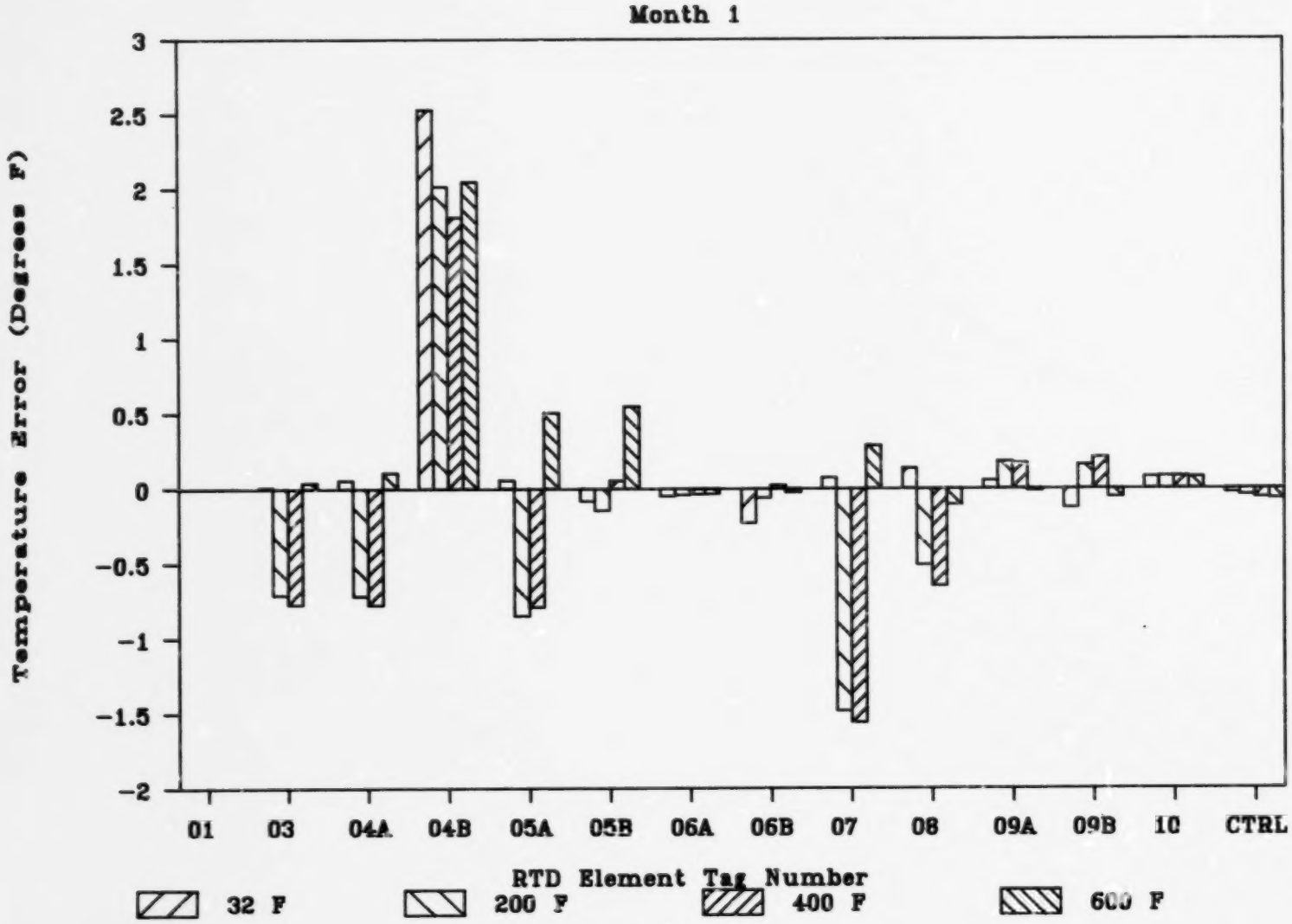

Figure 5.4. Temperature drift in the RTDs after one month.

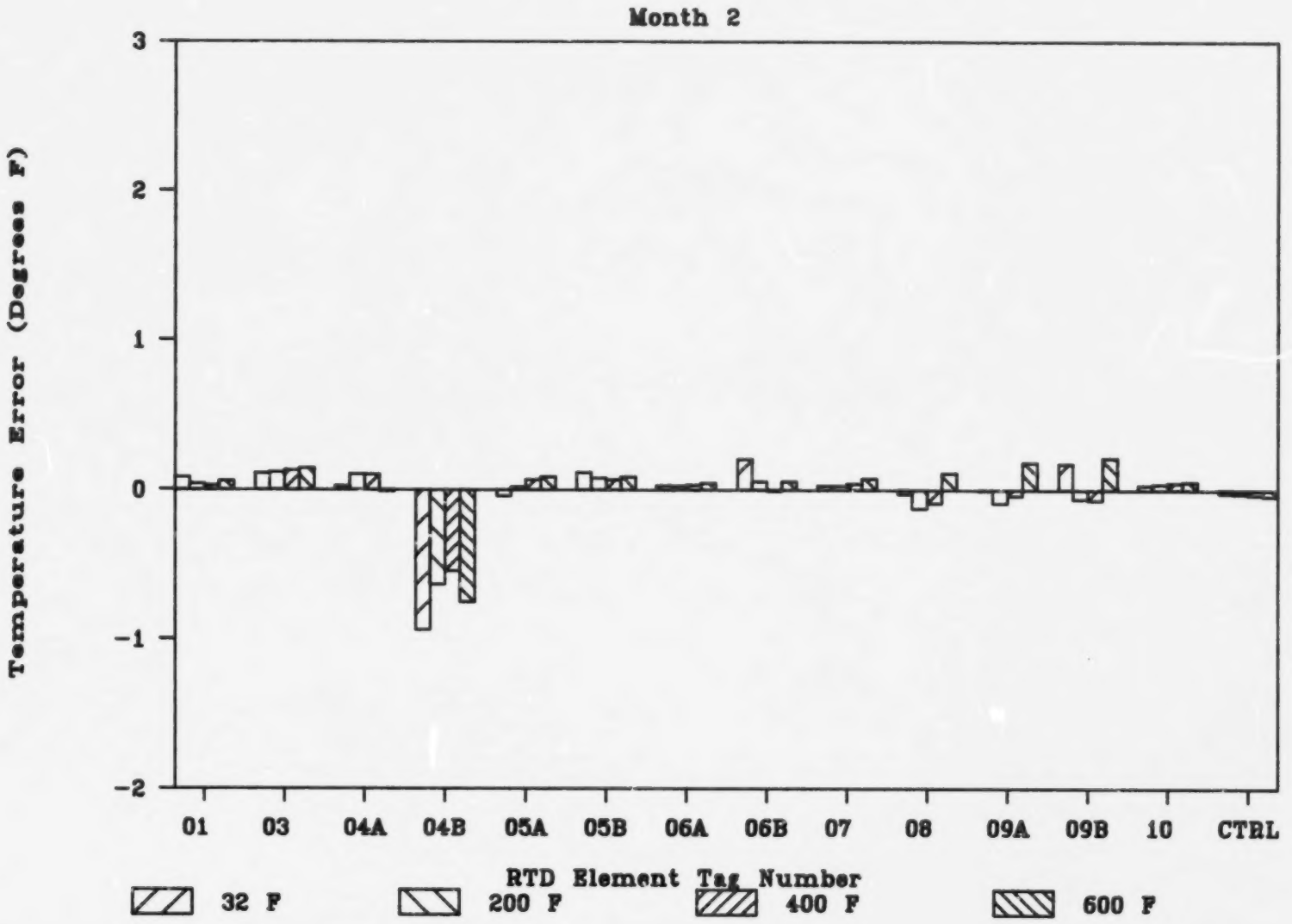

Figure 5.5. Temperature drift in the RTDs during second month.

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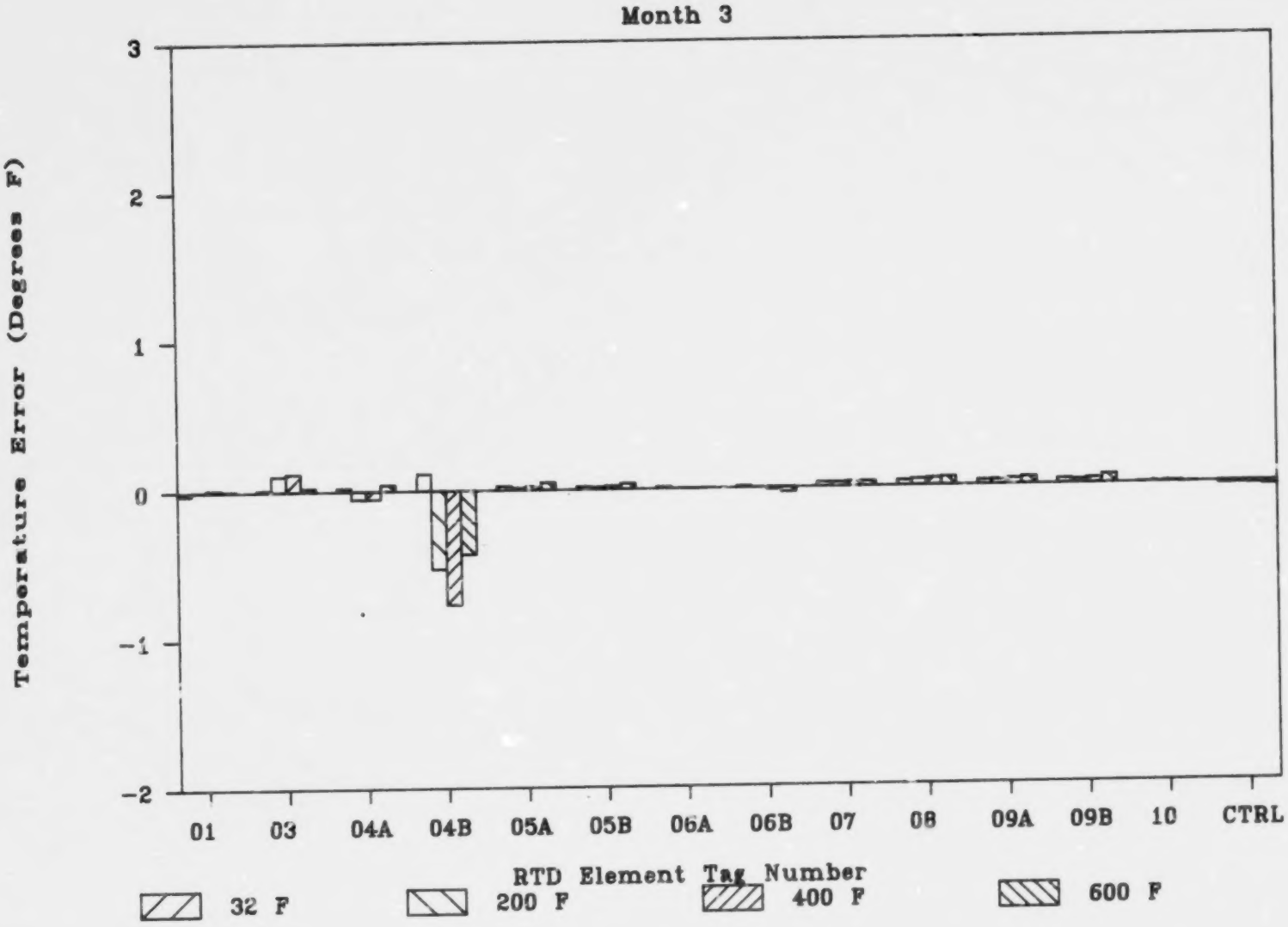

Figure 5.6. Temperature drift in the RTDs during third month.

1. calibrate each sensor at the ice point and three other temperatures between the ice point and about 600°F (315°C)

2. place the sensor in the furnace at 637°F for approximately one month

3. remove sensor from furnace and calibrate per Step 1 above

4. fit R vs T data to the Callendar equation

5. use the Callendar equation with fitted coefficients to evaluate the resistance of 32°F, 200°F, 400°F and 600°F

6. calculate the difference between the temperature obtained from the original calibration and the current calibration.

Figure 5.4 shows the changes which occurred in the indication of each RTD after one month of thermal aging. For example, RTD number 03 showed very little change at 32°F, but it read between -0.5 to -1°F low at 200°F and 400°F while at 600°F it only had about +0.1°F error. Element number 04A is the one that showed the largest error at all four temperatures (between 1.5°F to 2.5°F high). Element number 06A was the most stable RTD with very little change at all temperatures. Note that the changes in the indication of the reference sensor (CTRL) is very small indicating good repeatability for the calibration system. RTD number 01 was not in the program during the first month.

Figures 5.5 and 5.6 show the changes that occurred during the second and third months respectively. The changes represent one-month drift from the beginning to the end of the second month (Figure 5.5) and from beginning to the end of the third month (Figure 5.6). It is apparent that the calibration of all RTDs stabilized after the first month. The changes are much smaller during the second month and even smaller during the third month. The combined changes are shown in Figure 5.7 indicating that after three months of thermal aging the RTDs drifted by up to about 1°F except for RTD number 04B and 07 whose errors were in the 1°F to 2°F range.

The calibration data were also used to obtain the deviations in α, δ and R_0 (the parameters of Callendar equation used for fitting the data). The data are plotted in Figures 5.8, 5.9 and 5.10. Each plot provide the changes during first, second, and third month for all the RTDs tested and the CTRL RTD. These plots support our earlier conclusion that most of the shift in the calibration of the RTDs occurred in the first month and that the RTDs stabilized in the second and third month.

The insulation resistance (element to sheath) of each RTD was also measured each month after the RTD was removed from the furnace. These were measured at ambient temperature with 100 VDC applied across the sensor sheath and one of the RTD leads. The values were generally above the acceptable value of 100 megohms and remained so during the program.

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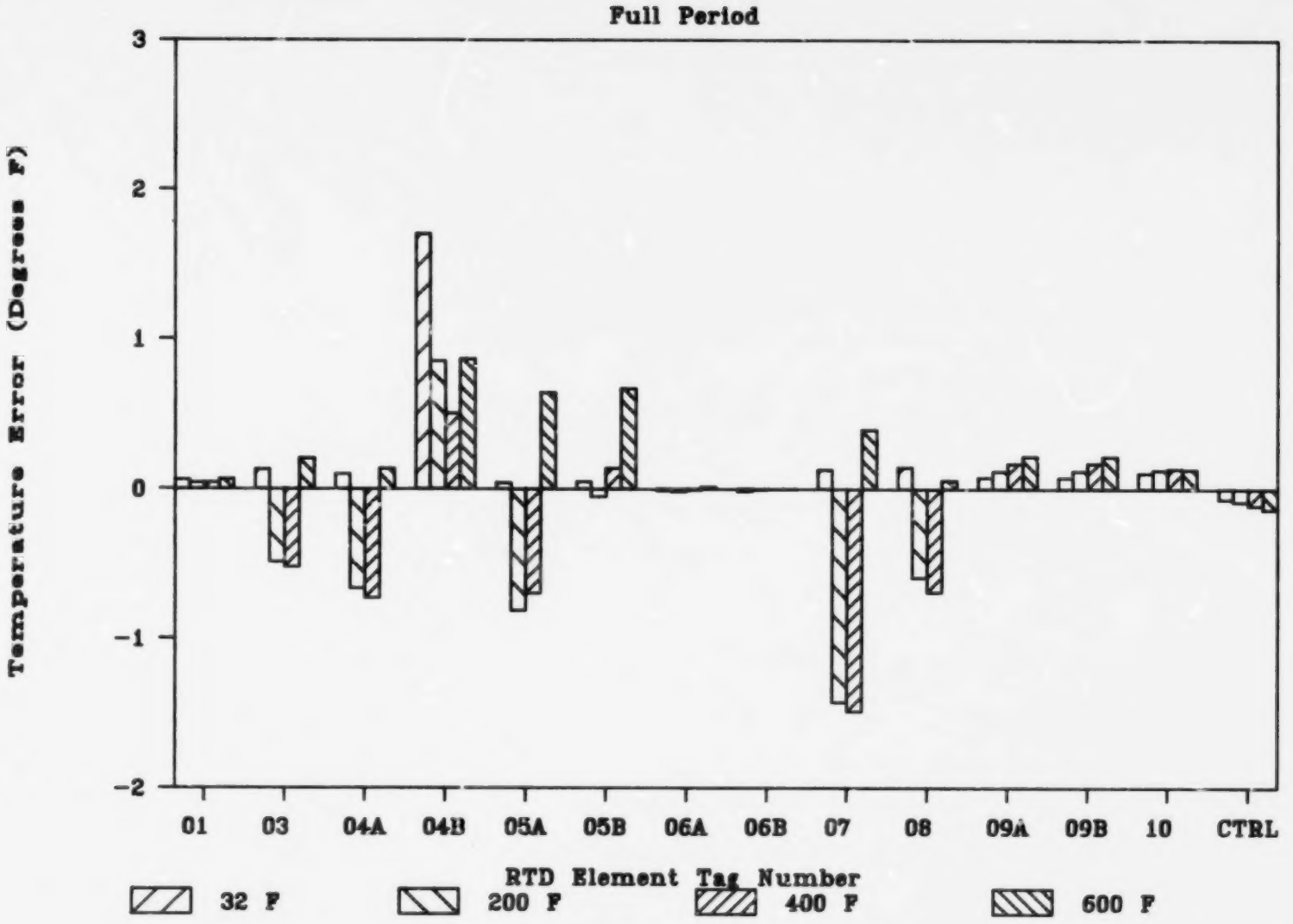

Figure 5.7. Temperature drift in RTDs for three months of thermal aging.

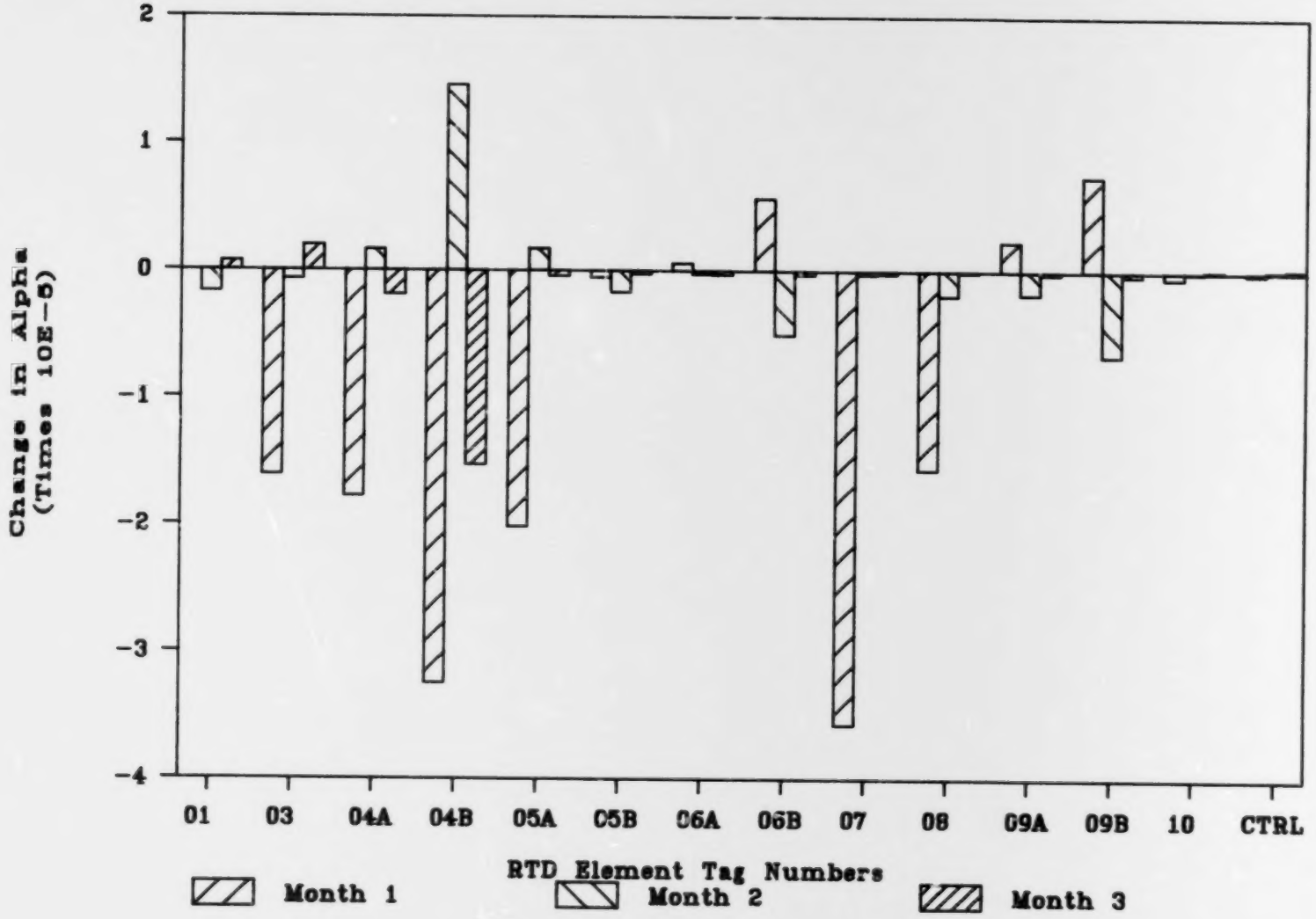

Figure 5.8. Changes in alpha for the RTDs.

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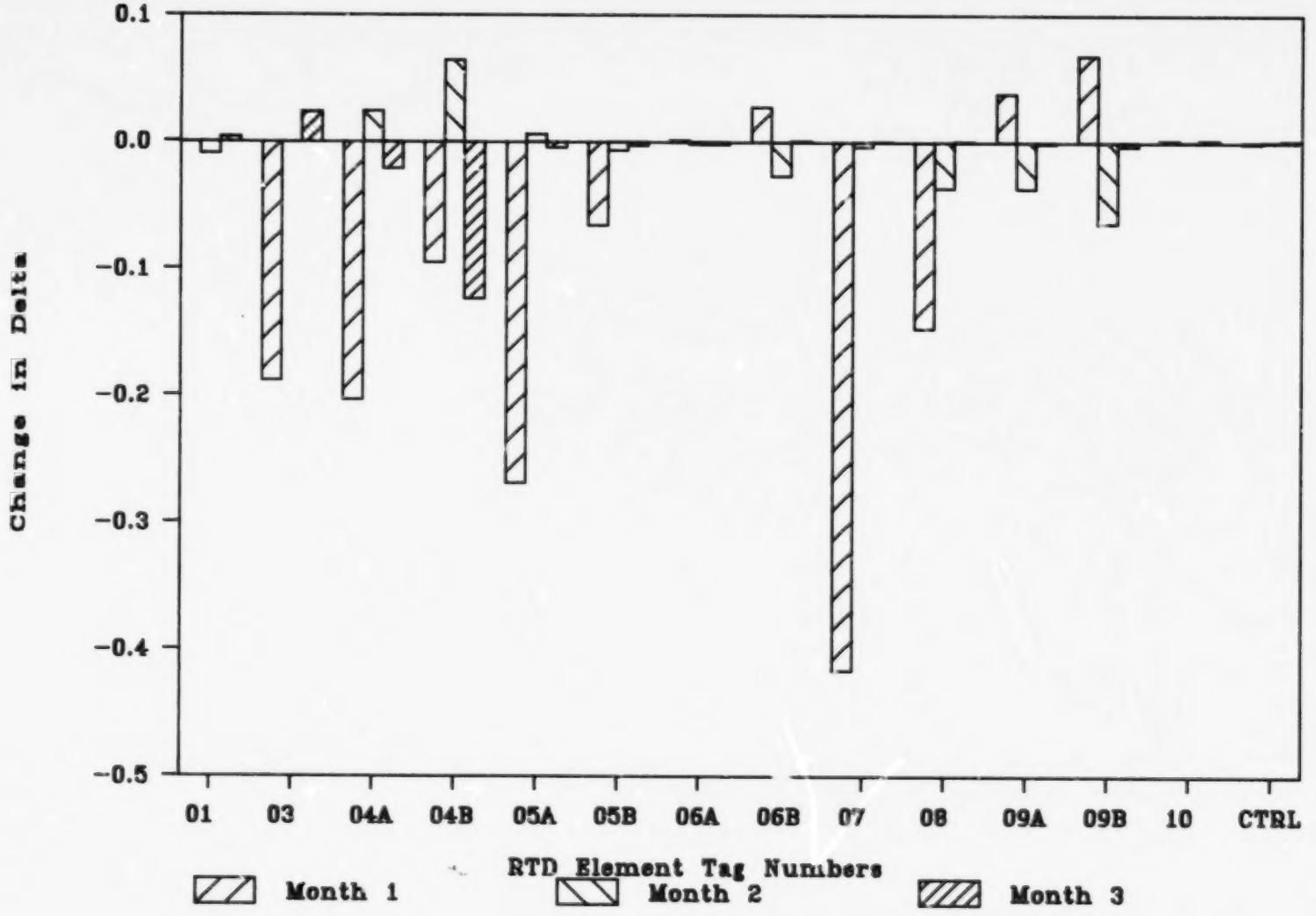

Figure 5.9. Changes in delta for the RTDs.

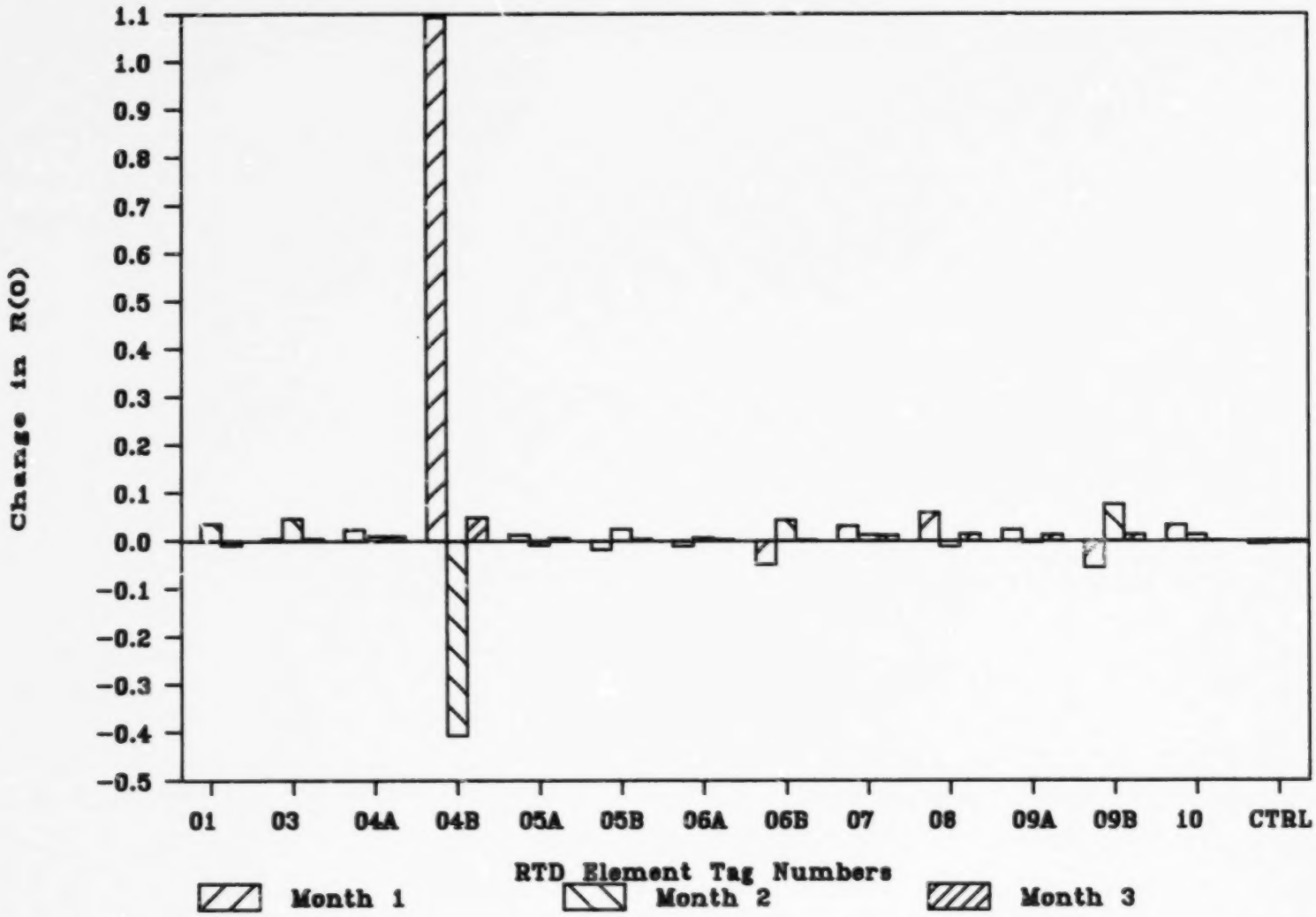

Figure 5.10. Changes in ice-point resistance for the RTDs.

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5.3 Dynamic Tests

Plunge tests were performed on all sensors before the start of exposure to simulated LWR conditions and again after a three month exposure. The results are summarized in Table 5.2. Note that only one element of RTD number 04 and 09 was tested and that the well-type RTDs were tested without a thermowell.

These results showed that the exposure to simulated LWR conditions had little or no effect on time response. This is consistent with extensive AMS experience in measuring the time response of sensors in operating nuclear power plants. This experience shows that although time response problems are common, they are predominantly the result of imperfect fits between sensors and thermowells for well-type RTDs.

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TABLE 5.2

Response Time Test Results

Tag #	Time Constant (sec) Initially	After 3 Months
01	2.1	2.1
03	1.4	1.4
04	2.1	2.0
05A	1.2	1.1
05B	1.4	1.3
06A	1.9	1.7
06B	1.8	1.6
07	1.0	1.1
08	3.5	3.2
09	2.7	2.5
10	0.9	0.9

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6. IN-SITU TESTING METHODS

This section reviews the current status of in-situ testing for calibration checking and response time checking.

6.1 Calibration Checking

Research has been in progress for several years on the use of Johnson Noise techniques to perform a one point calibration check while the RTD remains installed in a normally-operating plant. The principle is that temperature dependent voltage and current fluctuations occur in any resistor because of statistical variations in the spatial free electron population. It has been shown that temperature can be determined by monitoring these statistical fluctuations. The measurement has great appeal because it does not depend on the material properties of the resistor. It requires integration over a period of time to process the signals and obtain an estimate of the temperature. Longer processing times give better accuracy. The physics underlying this measurement technique has been known for almost fifty years, but practical implementation required two new developments: amplifiers capable of handling very low level signals (nanovolts and nanoamps) and a means to handle the filtering effect of cables between the sensor and the amplifier. Advances in the technology (mainly by Blalock, Shepard and Roberts at Oak Ridge National Laboratory and Brixy of West Germany) have furnished the instrumentation and several methods to deal with the cable effects. Three approaches are possible for overcoming the cable problem:

- Perform the measurement at the head of the sensor. This eliminates the cable, but results in radiation doses for the workers. Of course, the worker could leave the area after set up while the signal processing proceeds.

- Perform measurements on every installed cable to provide a correction factor. This is a major effort whose cost effectiveness is doubtful.

- Use the same cable (fully characterized) for all measurements. It would be connected sequentially to each sensor. This would also involve some radiation dose, but probably less than measurements performed at the sensor head.

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It appears that Johnson Noise methods now may be able to achieve an accuracy of 1°F. While this is not as good as is needed, it is close enough to justify additional effort. Measurements would give a rough calibration check and would provide experience which would help stimulate future improvements.

6.2 Response Time Testing

In-situ response time testing has been available for about ten years. The loop current step response test (offered through testing service contracts by AMS) has been used in hundreds of plant tests and has been accepted by the NRC and is approved in ISA Standard 67.06. The method involves passage of electrical current (40 to 80 ma) through the sensor leads to induce a measurable temperature transient (maximum change of 5 to 10°C). This internal heating transient record is then processed on a computer to transform the result into the response which would have followed a fluid temperature change. Laboratory tests show that the typical accuracy of the result is about ten percent.

Methods have also been developed which use the normal statistical fluctuations in a sensor's output to obtain a response time estimate. The situation is shown in Figure 6.1. The statistical properties of the output depend on two quantities: the statistical properties of the process temperature fluctuations and the sensor dynamic characteristics. An estimate of sensor dynamic characteristics can be obtained if a valid characterization of the statistical properties of the process temperature fluctuations can be obtained. Since this is not directly measurable, the statistical properties of the process temperature are assumed to have some standard feature (such as white noise). This facilitates the measurement, but it constitutes an unverifiable assumption which compromises the method's suitability for qualifying safety system sensors.

Another way to use noise analysis is as a degradation monitor rather than as a quantitative method for measuring response time. The idea is that a change in the output must be due either to a change in the process or a change in the sensor. Consequently, absence of change in the output is taken as evidence that neither the process nor the sensor have changed. If this approach is used, then a quantitative test (such as a loop current step response test) should be used to determine whether the change is due to the process or the sensor.

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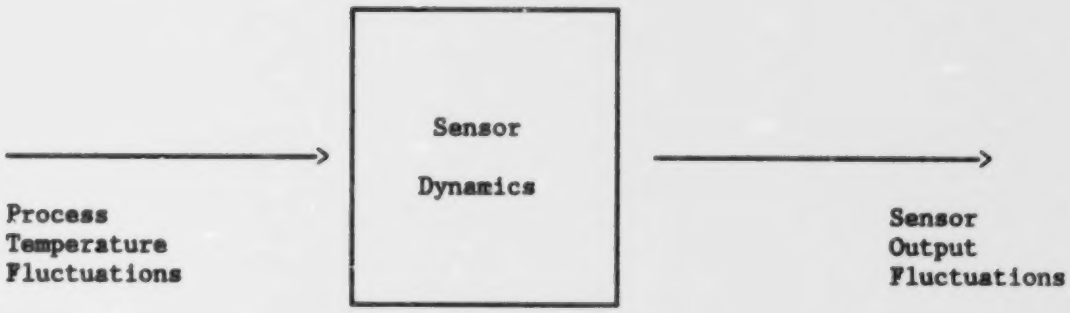

Figure 6.1. Sensor input-output processing of fluctuating signals.

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7. CONCLUSIONS AND RECOMMENDATIONS

The goals of the Phase I program were met and exceeded. The key results are:

1. Industry Survey - An informal, limited survey showed that performance requirements on nuclear plant ranged from 0.02°F (0.01°C) to 2.5°F (1.4°C) on calibration accuracy and 4 sec to 15 sec on response time.

2. A program was developed and implemented for drift testing of nuclear grade RTDs. Thirteen sensors were tested at LWR temperatures and calibration shifts of as much as 1.8°F (1.0°C) were observed.

3. Methods for in-situ calibration checking and response time testing were evaluated. The Johnson noise method appears ready for field evaluation since it now has the potential for calibration checking to within 1.0°F(0.6°C). For response time testing, the loop current step response method is fully suitable for measuring sensor time constants. Noise analysis may be suitable for detecting changes in response time (degradation testing).

In addition a review was performed to document known information pertinent to setting performance limits and testing intervals (See Appendix A). The results of that study are the following recommendations:

1. Re-examine tolerances on temperature measurements. Some are extremely tight and probably do not reflect real needs or real capabilities of industrial temperature sensors.

2. Initiate a burn-in program for new sensors.

3. Initiate a program of routine, simple tests to check for sensor problems.

4. Initiate a program of scheduled sensor removal and recalibration.

5. Develop a better data base of information about degradation mechanisms, their magnitudes, and their rates. This will

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involve theoretical work, single effects experiments, and long-term testing of typical RTDs.

6. Initiate a policy of avoiding a single sensor design in making redundant measurements.

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APPENDIX A

PERFORMANCE OF PLATINUM RESISTANCE THERMOMETERS IN NUCLEAR POWER PLANTS

This appendix contains an AMS review paper written for this project. The words RTD, PRT, and sensor are used in this appendix and the main report interchangeably.

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ABSTRACT

Basic design features and operating characteristics of platinum resistance thermometers and associated instrumentation are reviewed. Factors which affect the accuracy of new sensors and sensors with long-term exposure to nuclear power plant operating conditions are described. It is concluded that satisfying some currently-imposed tolerances may be unachievable and that new sensor evaluation and testing programs should be implemented to check long-term performances.

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1. INTRODUCTION

Over the last twenty to twenty-five years, resistance thermometry has become well established in industrial temperature measurement. Platinum resistance thermometers (PRTs) have been used much longer for precision measurements in standards laboratories, but adaptation for industrial use required development of rugged sensor designs which could tolerate harsh environments.

There is an essential compromise between ruggedness and performance (accuracy and stability) for PRTs. Numerous studies have been performed on effects which can cause decalibration of PRTs, but there have been few overview reports written for the non-specialist user rather than for the thermometry specialist. Also, there is surprisingly little published quantitative information on drift of PRT calibrations in industrial environments. This information is essential for establishing reasonable tolerances, recalibration schedules, replacement schedules, and requirements for in-situ testing for performance degradation. This report is intended to document the current knowledge base on industrial PRT performance and to identify current important gaps in this knowledge base.

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2. WHY MEASURE TEMPERATURE?

Temperature is one of the most commonly measured quantities in industry. However, a little reflection reveals that temperature itself is often of limited interest. Temperature usually is a convenient-to-measure quantity which is somehow related to a desired, but nonmeasurable quantity such as product yield, process efficiency, heat transfer rate, heat removal capacity or approach to metallurgical limits. Consequently, tolerances on temperature measurement accuracy should involve consideration of the relation between temperature and the quantity of interest:

$$\Delta T = (\delta T/\delta M)\, \Delta M \qquad (1)$$

where

ΔT = tolerance on temperature measurement;

ΔM = tolerance on desired quantity; and

$\delta T/\delta M$ = sensitivity of changes in T to changes in M.

The sensitivity, $\delta T/\delta M$, may be very simple or very complex. For example, tolerance on temperature measurements for nuclear plant safety systems may actually be intended to defend against departure from nucleate boiling or excessive fuel center line temperature. In these cases, the relation between coolant temperatures and the quantity of interest may require analyses using detailed computer programs for a variety of occurrences of potential importance. The uncertainty in this analysis should be considered in establishing reasonable tolerances on the temperature sensors.

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3. PRT OPERATION

Industrial PRTs exploit the temperature dependence of the resistivity of almost-pure platinum to measure temperature. Because complete elimination of trace elements in refined platinum is difficult, industrial PRTs use platinum doped with rhodium to achieve material which can be prepared reproducibly at reasonable cost.

Figure 3.1 shows the resistance relative to its value at 0°C for industrial PRT grade platinum. Clearly, the resistance-temperature relation is almost linear. If we temporarily ignore the small curvature, we may write:

$$\frac{R(T)}{R_0} = 1 + \alpha T \qquad (2)$$

where

$R(T)$ = resistance at temperature, T(°C)

R_0 = resistance at 0°C

α = slope of R/R_0 vs T line

Since the relationship is not exactly linear, the average slope would vary over different portions of the curve. By convention, α is the average slope between 0 and 100°C:

$$\alpha = \frac{R(100°C)/R_0 - R(0°C)/R_0}{100}$$

$$= \frac{R(100°C)/R_0 - 1}{100}$$

$$= \frac{R(100°C) - R_0}{100}$$

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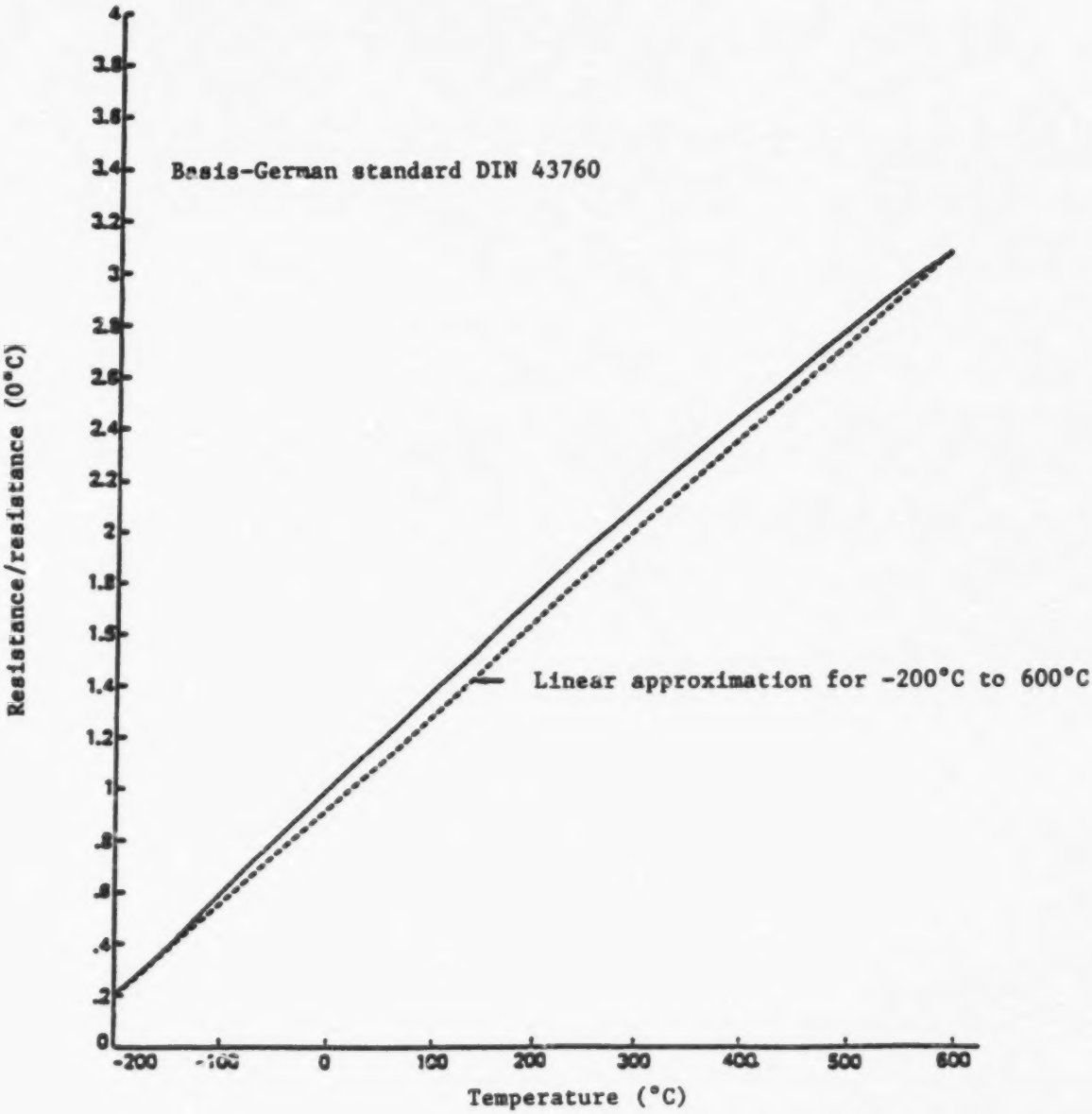

Figure 3.1. Resistance vs. temperature for industrial grade platinum.

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Typical values of α are 0.003925 for pure platinum (used in PRTs for standards work), and 0.00385 for industrial PRTs. Highest values of α occur for purest platinum.

Now, let us modify the resistance vs temperature formula to account for the curvature. A straightforward mathematical approach is to use as many terms in a Taylor series as required to obtain suitably small errors:

$$R/R_0 = 1 + a_1T + a_2T^2 + \ldots \qquad (3)$$

This has been done; and, until recently, the accepted form is second order for temperatures above 0°C

$$R/R_0 = 1 + a_1T + a_2T^2$$

Typical values for industrial PRTs are

$$a_1 = 0.003907$$

$$a_2 = -5.737 \times 10^{-7}$$

The most common form of the R/R_0 vs T relation is an alternate form of the second-order equation. It retains the parameter α, the average slope between 0 and 100°C. The form is:

$$R/R_0 = 1 + \alpha \left[T - \delta\left(\frac{T}{100} - 1\right)\left(\frac{T}{100}\right)\right] \qquad (4)$$

Note that the last term in the bracket disappears when T = 0°C and T = 100°C:

$$\frac{R(0°C)}{R_0} = 1$$

$$\frac{R(100°C)}{R_0} = 1 + \alpha(100)$$

This form permits characterization of the PRT by the ice point (R_0), the average slope for the range, 0 to 100°C (α), and a factor (δ), which accounts for the curvature. A typical value of δ is 1.49 for industrial PRTs.

For temperatures below 0°C, another term was added to account for the increased curvature in that range:

$$\underline{R} = 1 + \alpha[T - \delta(\frac{T}{100} - 1)(\frac{T}{100}) - \beta(\frac{T}{100} - 1)(\frac{T}{100})^3] \quad (5)$$

The coefficient, β, has a value of zero for temperatures above 0°C and a non-zero value (typically 0.1) for temperatures below 0°C. Equation 5 is called the Callendar-van Dusen equation.

The Callendar-van Dusen equation (or its equivalent, Eq. 4 for temperatures above 0°C) has been used extensively as the form for defining the R/R_0 vs T relation for PRTs. However, work on defining the temperature scale and interpolating with standard-grade PRTs, revealed errors of as large as 0.042°C in the 0 to 630°C range. A correction was developed for standard-grade PRTs to deal with this error while retaining the familiar form of the functional relations. The resulting relations for temperatures above 0°C are

$$R/R_0(T') = 1 + \alpha[T' - \delta(\frac{T'}{100} - 1)(\frac{T'}{100})] \quad (6)$$

$$T = T' + 0.045(\frac{T'}{100})(\frac{T'}{100} - 1)(\frac{T'}{419.58} - 1)(\frac{T'}{630.74} - 1) \quad (7)$$

where

T' = fictitious temperature

T = true temperature (according to the International Practical Temperature Scale of 1968)

The new correction term is often called the "Moser wobble." The correction vs temperature is shown in Figure 3.2. Clearly, this correction is often insignificant compared to typical industrial tolerances and may be omitted in those cases. It is not clear that this correction developed for standards-grade PRTs (pure platinum) is applicable for industrial PRTs (platinum doped with rhodium).

The R/R_0 vs T relation is both intensive and extensive in nature. The resistance at any temperature depends on the resistivity (a material characteristic, therefore an intensive property) and the amount and configuration of platinum present (an extensive feature). It is appropriate to think of R_0 as a feature determined by manufacturing procedures. The quantities, α and δ (or a_1 and a_2) are determined only by the properties of the platinum.

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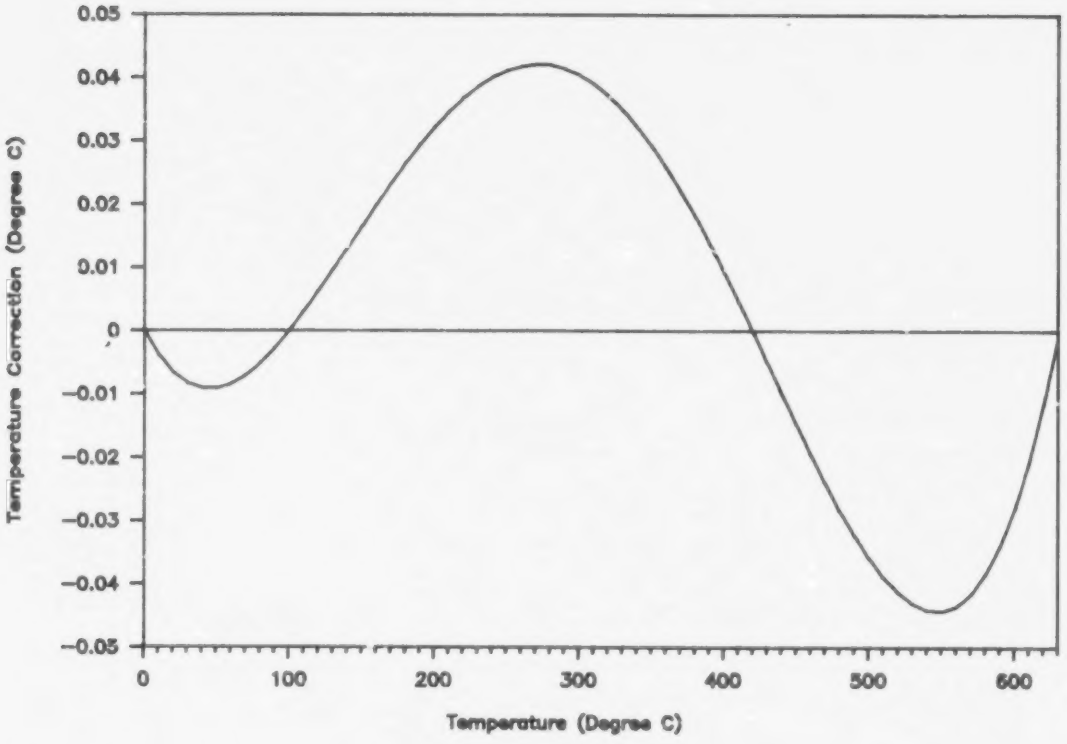

Figure 3.2. Correction vs. temperature.

Manufacturers adjust the amount and configuration of platinum to obtain certain standard values for R_0. Most industrial PRTs have R_0 values of 100 ohms. Less common but available, values of R_0 are 25, 200, and 500 ohms. The platinum in a PRT is formed as a thin wire or a thin film. Some available configurations are shown in Figures 3.3 through 3.5. Platinum has an approximate ice point resistivity of 1.1×10^{-5} ohm cm. This information permits evaluation of approximate length needed to achieve a desired ice point resistance. For example, a wire with a diameter of 0.05 mm would need to be 178 cm long to give a resistance of 100 ohms. Since several modes of decalibration are surface effects, it is important to consider the surface area associated with a wire of a specific diameter to achieve a desired total resistance. The surface to resistance ratio and length to resistance ratio are given by:

$$S/R = C_1 D^3 \tag{8}$$

$$L/R = C_2 D^2 \tag{9}$$

where

$C_1 = \pi^2 \times 10^5/4.4$ for platinum with resistivity of 1.1×10^{-5} ohm cm

$C_2 = \pi \times 10^5/4.4$

S = surface area (cm^2)

R = resistance (ohms)

L = wire length (cm)

D = wire diameter (cm)

This shows that small diameter wires are desirable to reduce the wire length needed to achieve a specific resistance and to decrease surface area. Consequently, there is a conflict between considerations of ruggedness (large wire diameter) and insensitivity to surface contamination (small wire diameters).

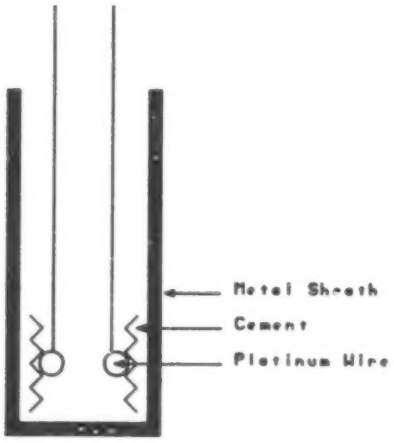

Figure 3.3. A wall-mount PRT.

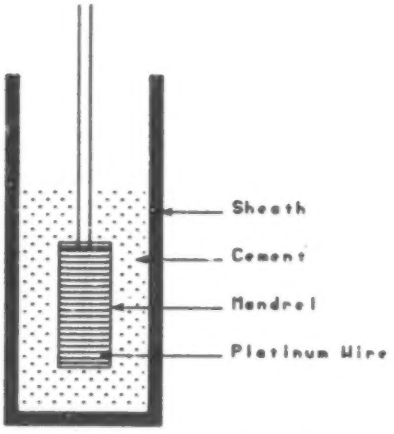

Figure 3.4. A Mandrel-mount PRT.

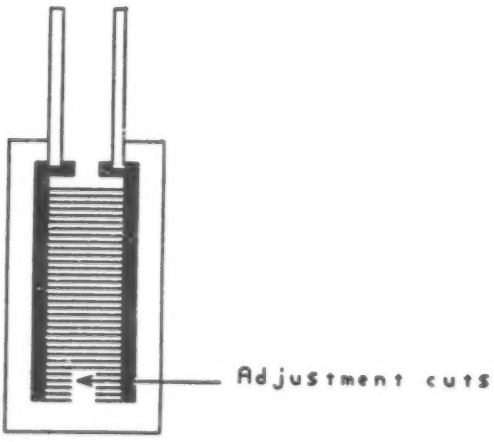

Figure 3.5. A film-type PRT.

4. PRT CALIBRATION

Platinum resistance thermometers are calibrated using the following procedure:

1. Measure the resistance at three or more known temperatures above 0°C. Also, measure the resistance at one or more known temperatures below 0°C if the sensor is to be used at temperatures below 0°C. The known temperatures may be achieved in a melting point cell (where nature determines the temperature) or in a constant temperature bath (where the temperature is provided by a calibrated, traceable, standard thermometer).

2. Fit the data to the appropriate equation. (Equation 3 or, equivalently, Equation 4 for calibrations above 0°C. Equation 5 for calibrations which include points below 0°C.) This gives the coefficients which apply for the sensor being calibrated.

3. The equation with the fitted coefficients is then used to generate a calibration table.

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5. INHERENT ERRORS IN TEMPERATURE MEASUREMENTS WITH PRTs

5.1 Heat Transfer Effects

There are four steady-state heat transfer effects which can affect the accuracy of temperature measurements with PRTs: internal heating, stem losses, radiative exchanges, and flow-induced heating. The last two are generally not important in nuclear plants. Radiative exchanges are important only for cases where the sensor is in a line-of-sight position relative to a much hotter or colder body with a transparent intervening medium. The only reactor type where this might be important is the HTGR. Flow-induced heating is significant only for very high velocity flows (Mach 1 and greater). The first two effects should be considered in assessing PRT accuracy in nuclear plants.

Internal heating occurs because of Joule heating (I^2R) due to passing an electric current through the sensor or because of radiation absorption. The sensing current used in sensors is set to a low value (typically 1 ma) in order to ensure small self heating errors. The self heating error is given by:

$$T = \frac{(SHI)I^2R}{R_0\alpha} \qquad (10)$$

where

T = temperature error

SHI = self-heating index (resistance change per watt of power generated in the sensor)

I = current through sensor

R = resistance of the sensor element.

α = sensor calibration

Typical values of SHI are 5 to 10 ohms per watt for sensors installed in flowing water. Self-heating effects are typically 0.001 to 0.02°C for PRTs in flowing water. Higher errors occur in poorer heat transfer environments such

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as still air. Self-heating effects always cause the indicated temperature to be too high. However, this does not mean the self heating will always cause readings to be too high. For example, calibrations are often made in environments where the surface heat transfer is poor (i.e., ice bath, stirred oil, stagnant air). In that case, the self-heating effect would be greater during calibration than during normal use. Consequently, the lower self heating during normal operation would cause a negative measurement error.

Absorption of gamma rays or neutrons can result in self-heating errors. This effect should be small for out-of-core sensors in nuclear power plants. The temperature measurement error is given by

$$T = \frac{(SHI)Q}{R_0\alpha} \qquad (11)$$

where

$\dot{Q}$ = heating due to absorbed nuclear radiation.

The evaluation of $\dot{Q}$ requires specific information on radiation flux, radiation energy, and radiation absorption cross sections. Flux fields in typical sensor locations are difficult to estimate well enough to permit accurate error assessments.

Stem losses are measurement errors caused by heat transfer along the sensor sheath as a result of temperature differences between the sensor tip and the sensor head. The situation is illustrated in Figure 5.1. The stem loss occurs because of competition between axial and radial heat transfer resistances (see Figure 5.2). For small stem loss errors, the following condition must be satisfied:

$$(R_{RI} + R_{RS}) \ll R_A,$$

That is, the radial heat transfer resistance must be much smaller than the axial heat transfer resistance. Changes which can decrease stem loss errors are

1. Increased sensor length (increases R_A)
2. Decreased sensor diameter (decreases R_{RI})

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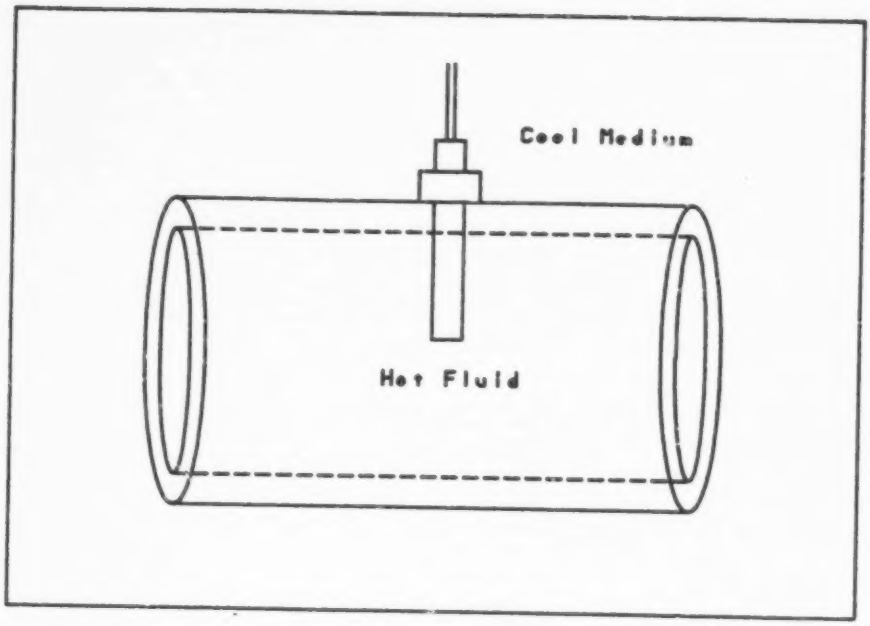

Figure 5.1. Sensor installation with potential stem loss errors.

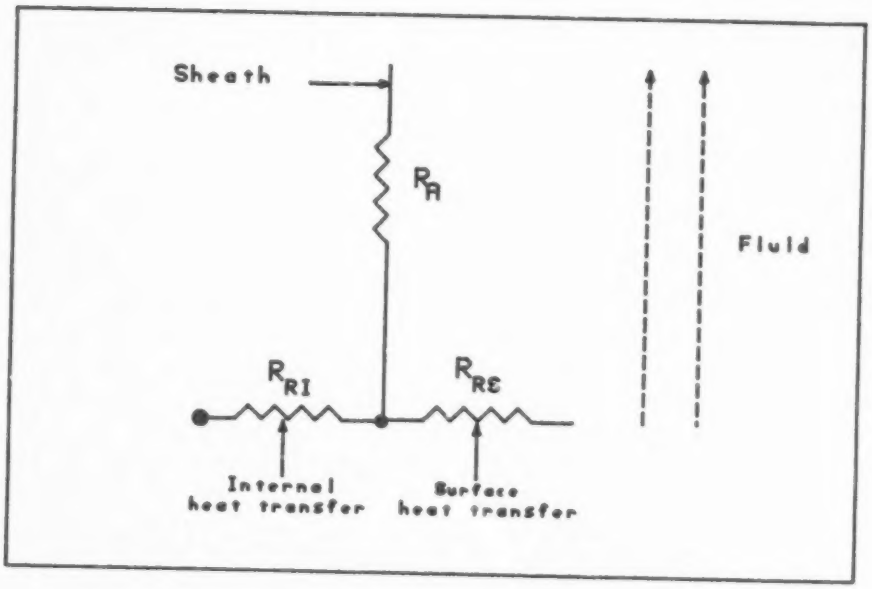

Figure 5.2. Axial and radial heat transfer resistances.

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3. Installation in fluid which results in improved surface heat transfer. For example, stem loss errors would be greater in stagnant fluid than in flowing fluid (decreases R_{RS}).

4. Insulation of sensor head. This would decrease the temperature difference which provides the driving force for heat transfer.

Formulas have been developed for estimating stem loss errors. Since these formulas are based on approximate models (homogeneous cylinders), the estimates are only rough approximations and should be viewed as rules-of-thumb rather than quantitative evaluations. The stem loss error formula is:

$$T = \frac{(T_H - T_F)\,(2\,k\alpha/h)}{[(1 + k\alpha/h)e^{-\alpha L} - (1 - k\alpha/h)e^{-\alpha L}} \qquad (12)$$

where

T = stem loss error (°C)

T_H = temperature of the sensor head (°C)

T_F = fluid temperature (°C)

k = thermal conductivity of the sheath (W/cm °C)

h = surface heat transfer coefficient on the sheath (W/cm^2 °C)

α = thermal diffusivity (cm^{-1})

L = sensor length (cm)

The formula may also be used to estimate the sensor length required to give a certain stem loss error. For example, if one chooses a maximum allowable stem loss error of 0.18%, the formula for the minimum length, L, is

$$L = 7\left[2r_0h/k(r_0^2 - r_i^2)\right]^{-1/2}$$

where

r_0 = sensor outer radius

r_i = sensor inner radius

More accurate stem loss estimates can be obtained using finite difference models. These permit explicit treatment of the actual structure of the sensor internals and couplings to surroundings. Computer solutions are required to obtain meaningful simulations. However, even in this case, uncertainties in as-built geometries and physical properties limit the accuracy of estimates. The best approach is to use large conservatism in evaluating stem loss effects.

5.2 Thermoelectric Effects

Thermoelectric voltages are produced when temperature differences occur over junctions of dissimilar metals. Dissimilar metal junctions always exist somewhere in circuits for platinum resistance thermometers. There is a certainty that a junction will occur where the platinum wire is connected to extension wire. This may occur in the head of the sensor if platinum is used for internal connectors between the sensing element and the leads which emerge from the sensor. It occurs inside the sensor sheath if base metal wires are used as lead wires inside the sensor. Situations even exist where more than one type of lead wire is used. For example, internal wires may be chosen on the basis for small temperature coefficients of resistivity (i.e. constantan), and connecting wires may be selected on the basis of strength and ductility (i.e. stranded nickel).

Thermoelectric voltages are produced in PRT circuits if the metal-to-metal transitions in the two legs of the circuit experience different temperatures. The voltage produced is given by:

$$V = S_{AB} \Delta T \qquad (13)$$

where

V = voltage produced,

S_{AB} = relative Seebeck coefficient between the two wire materials, and

ΔT = temperature difference between the two junctions.

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For example, the relative Seebeck coefficient between platinum and copper is about 30 microvolts per °C temperature difference between the two metal-to-metal junctions.

The magnitude of temperature differences between junctions will depend on sensor design characteristics and installation conditions. Some situations are shown in Figure 5.3.

The magnitude of the error due to thermoelectric effects may be evaluated by comparing the thermoelectric voltage to the voltage drop through the platinum resistance element. For example, a PRT with an R_0 of 100 ohms will have a sensitivity of about 0.385/°C. For a 1 ma sensing current, the change is 0.385 mv/°C. Therefore, a 1°C temperature difference across platinum-to-copper transitions will cause a 0.03 mv contribution and a 0.08°C error. In practice, errors as large as 1°C have been observed.

Measurement errors due to thermoelectric effects are easily identified in installed PRTs. The polarity of the thermoelectric voltage is reversed when the connections to the read-out instrumentation are reversed. Therefore, a change in apparent resistance (or indicated temperature) when lead wires are reversed is a sure sign that thermoelectric errors are present.

5.3 Electrical Shunting

Proper operation of a PRT depends on having adequate insulation resistance between the sensing element and the sheath. The equivalent circuit is shown in Figure 5.4. The measurable resistance is given by:

$$\frac{1}{R_m} = \frac{1}{R_s} + \frac{1}{2R_I} \qquad (14)$$

where

R_m = measured resistance

R_s = sensing element resistance

R_I = sensing element-to-sheath resistance

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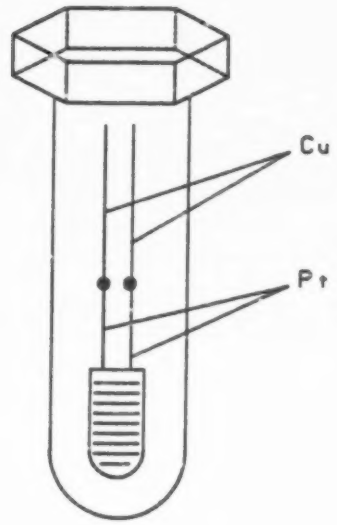
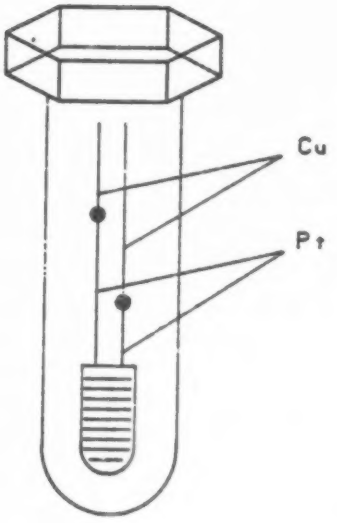
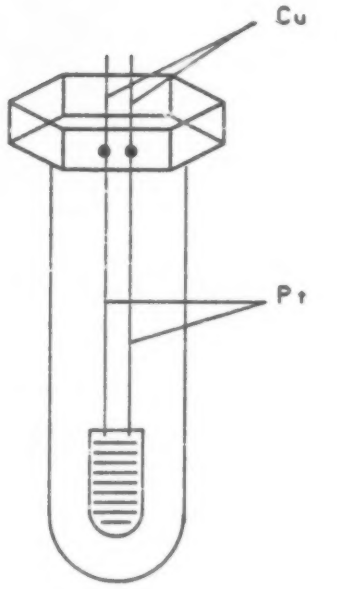


Thermoelectric effects unlikely. The only way junctions could experience different temperatures is for azimuthal gradients to exist around the sensor.



Thermoelectric effects are more likely. Gradients along the sensor length cause junctions to experience different temperatures.



Thermoelectric effects depend on temperature gradients across the housing at the sensor head. It is quite possible for gradients to occur in typical industrial installations.

Figure 5.3. Junctions thermoelectric effects in PRTs.

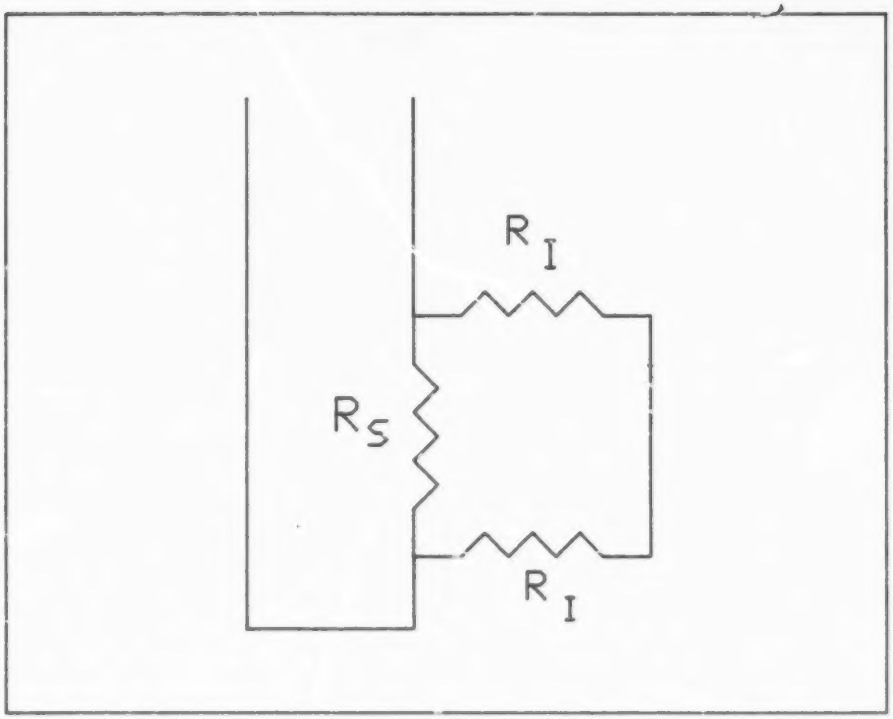


Figure 5.4. Shunting equivalent circuit.

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An estimate of the measurement error is given by:

$$T = \frac{-R_s/R_0}{\alpha(2R_I/R_s + 1)} \qquad (15)$$

The resistivity of insulators decreases dramatically as temperature increases. For example, the temperature dependence of the resistivity of magnesium oxide is shown in Figure 5.5. This shows that electrical shunting errors become larger as temperature increases. For example, consider a PRT with an R_0 of 100 ohms and an insulation resistance of 10 megohms. The electrical shunting error at 0°C is -0.001°C. At 300°C, R_s increases to 212 ohms and R_I decreases to approximately 10,000 ohms. Consequently, the electrical shunting error increases to -2.72°C at 300°C.

Of course, if a PRT is calibrated with a certain insulation resistance, then the same errors will occur in use so long as the insulation characteristics stay the same. A significant temperature dependent insulation resistance violates the basis for the validity of interpolating equations such as the Callendar-van Dusen equation. However, the largest concern is a reduction of insulation resistance because of moisture leaking in the sheath.

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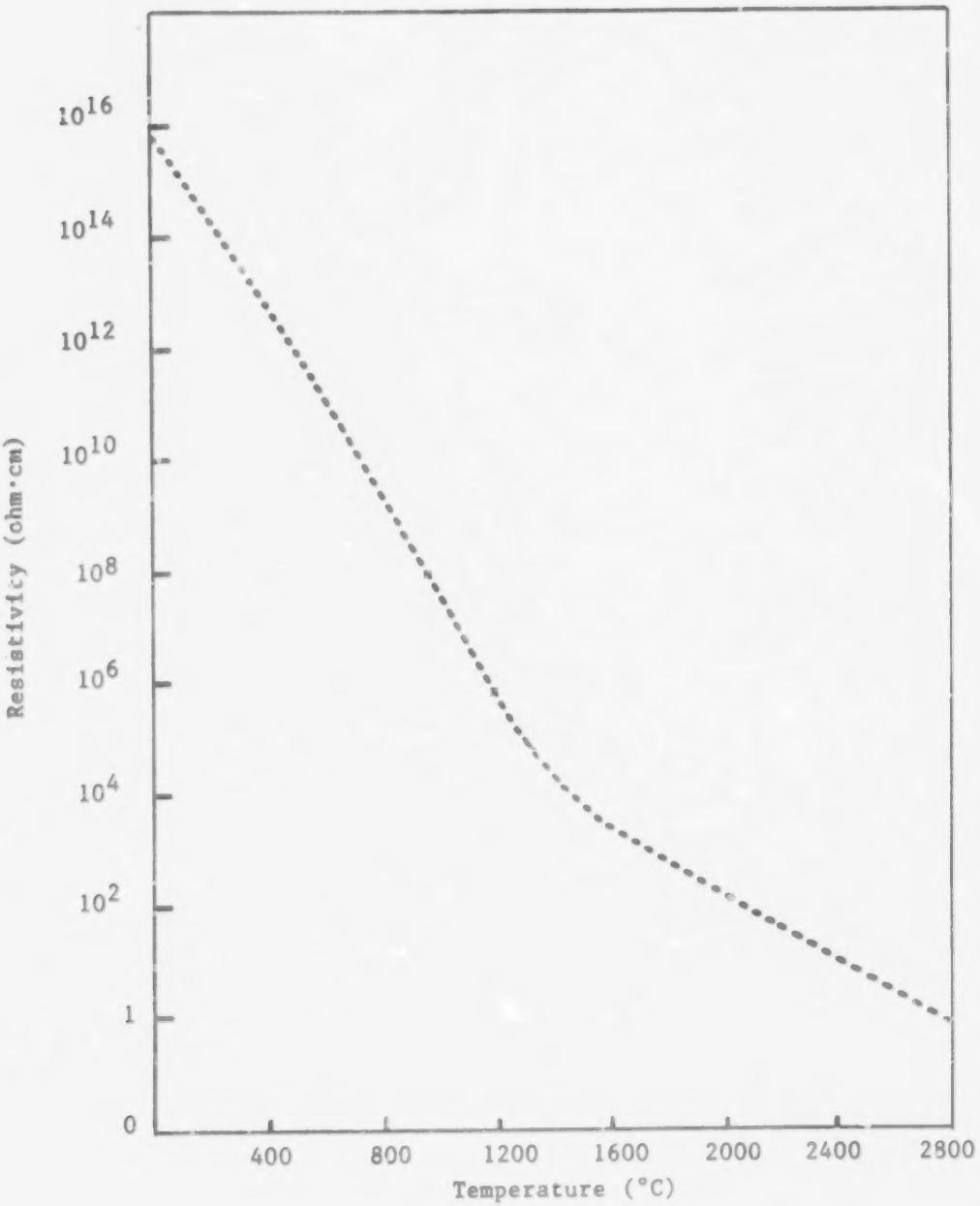

Figure 5.5. Temperature effect on resistivity of magnesium oxide.

6. PRT READ-OUT AND TRANSMITTERS

6.1 Principles

There are three main types of industrial instrumentation for transducing PRT resistance changes into a voltage signal which is proportional (at least approximately) to temperature. These are passive bridges, active bridges, and ohmmeter systems.

The passive bridge is shown in Figure 6.1. The voltage drop, E, is related to the PRT resistance, R_T, by:

$$E = E_o \frac{R}{(R + R_T)(R + R_s)} (R_T - R_s) \qquad (16)$$

The active bridge is shown in Figure 6.2. Basically, the active bridge uses a feedback circuit to introduce a voltage to the sensor arm of the bridge. This voltage is continuously adjusted to drive the bridge voltage, E, to zero. The feedback voltage is monitored to provide a measure of the sensor resistance.

The ohmmeter system is shown in Figure 6.3. Two of the four leads are connected to a constant current power supply and two are connected to a voltage measuring system. Ohm's law is used to provide the sensor's resistance.

6.2 Lead Wire Effects

Lead wires add significant resistance to PRT circuits unless the wires are very short. Consequently, it is essential to eliminate lead wire resistance contributions by appropriate instrumentation or wiring approaches. In order to permit lead wire compensation, PRTs are built in three-wire and four-wire configurations. The common configurations are shown in Figure 6.4.

The three-wire configuration is used in bridge circuits as illustrated in Figure 6.5. This arrangement places one lead wire in each of the two opposing arms of the bridge. In this case, the bridge equation is:

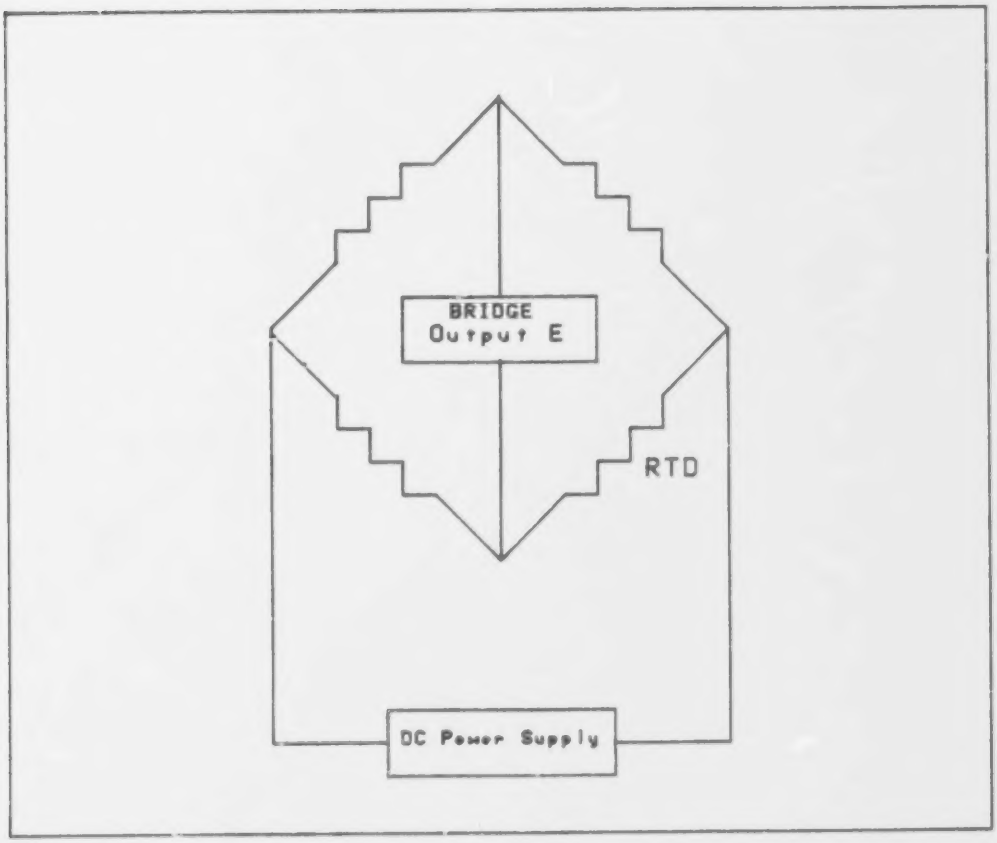

Figure 6.1. Passive Wheatstone bridge circuit.

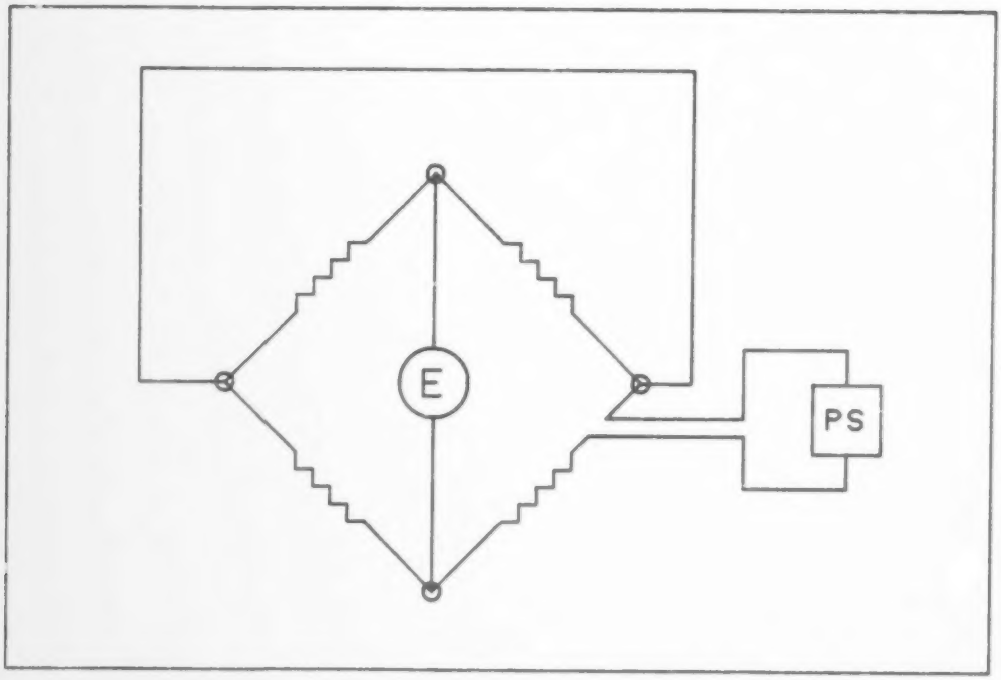

Figure 6.2. Active Wheatstone bridge circuit.

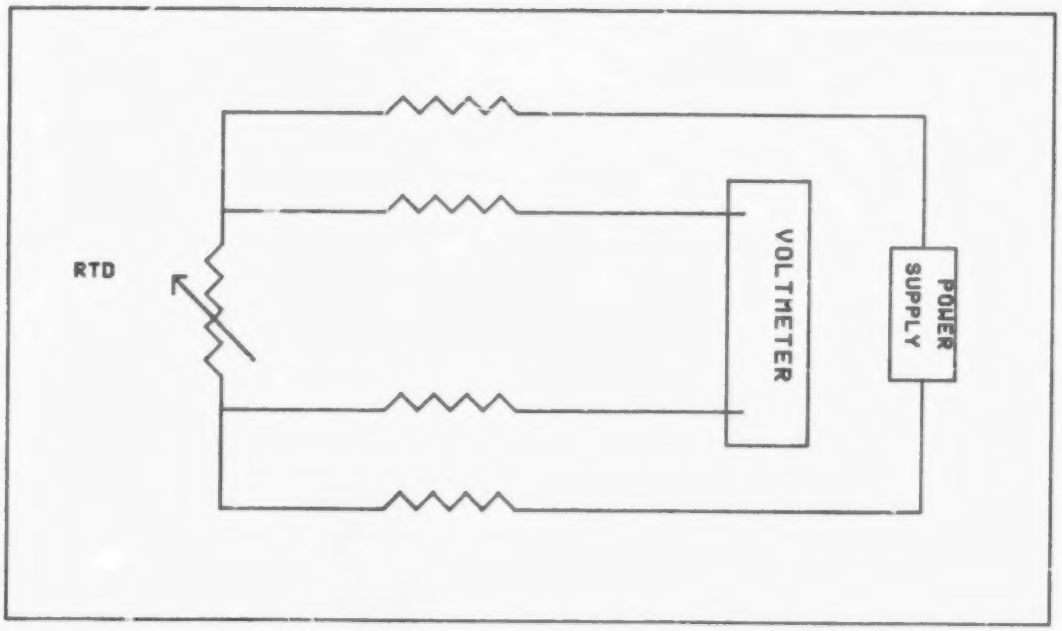

Figure 6.3. Ohmmeter system.

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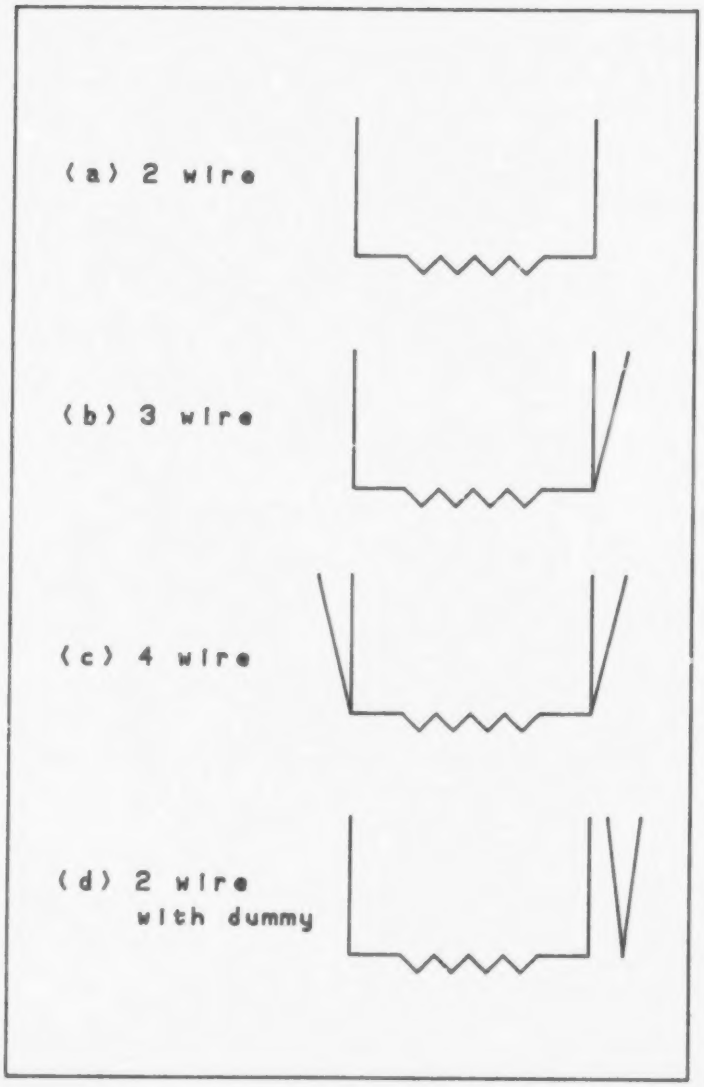

Figure 6.4. Lead wire configuration.

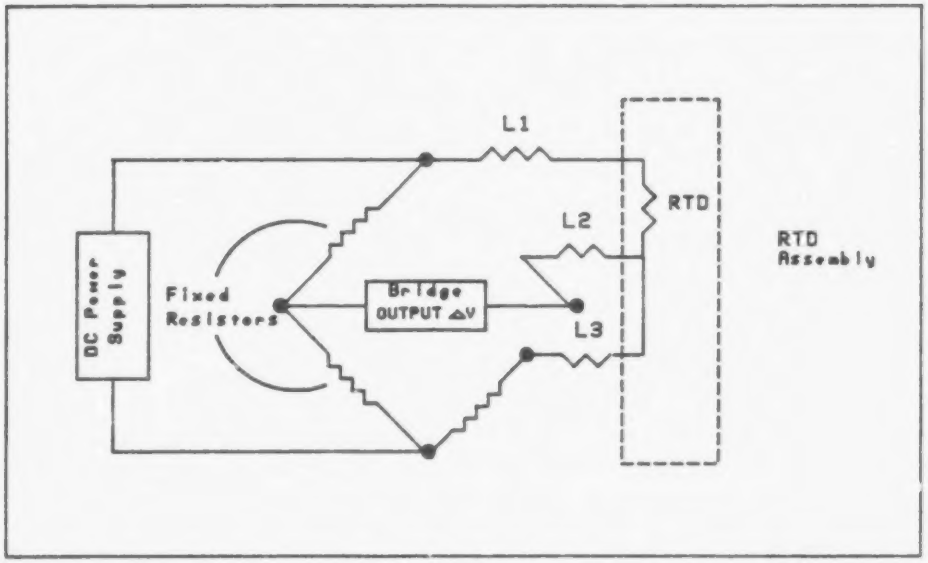

Figure 6.5. Wheatstone bridge circuit with 3 wire configuration.

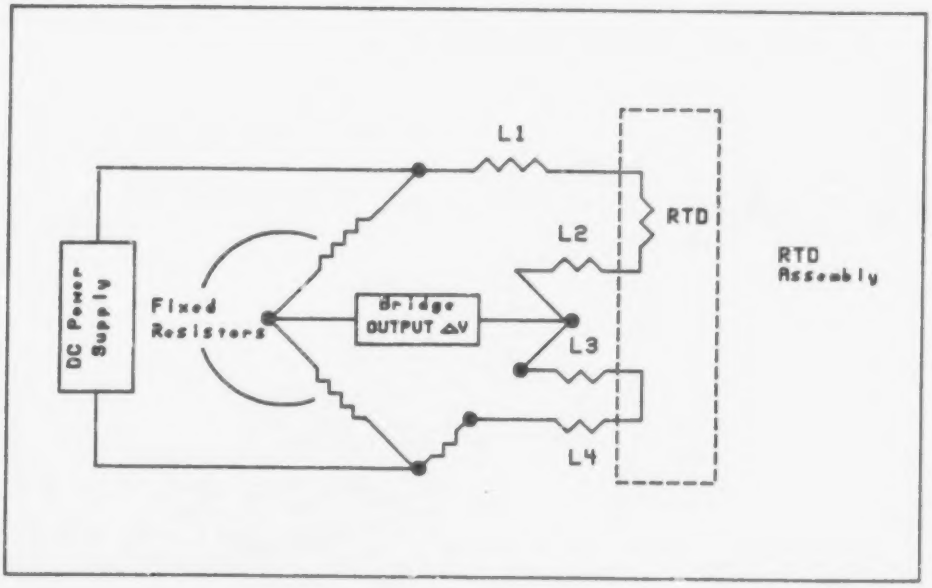

Figure 6.6. Wheatstone bridge circuit with 4 wire configuration.

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$$E = E_o \frac{R}{(R + R_T + R_L)(R + R_s + R_L)} (R_T - R_s) \quad (17)$$

Comparison with Equation 16 reveals that the lead wire resistances only contribute to the coefficient of the main temperature-dependent term. This is just a gain factor which is handled by calibration of the bridge.

The dummy lead four-wire configuration is shown in Figure 6.6. As for the three-wire configuration, this arrangement places the lead wires in opposite arms of the bridge. The bridge equation for this case is the same as Equation 17 except that R_L is replaced by $2R_L$ in the factors in the equation.

In the ohmmeter measurement system (see Figure 6.3), one lead on each side of the PRT is connected to a constant current power supply. The two remaining leads are used to monitor the voltage drop across the PRT. Since the voltage is measured with an instrument having high input impedance, there is insignificant current flowing in the measuring circuit, and consequently, insignificant voltage drop. In this case, zero and span are set by adjusting the bias and gain of the amplifier.

6.3 Bridge Nonlinearities

Ideally, a bridge would provide a voltage signal proportional to the PRT's resistance. That is

$$E = A + BR_T \quad (18)$$

Actual bridges have slight nonlinearities. For example, Equation 16 may be rewritten in a form which is similar to Equation 18:

$$E = \left[\frac{-E_0 R R_s}{(R + R_T)(R + R_s)} \right] + \left[\frac{E_0 R}{(R + R_T)(R + R_s)} \right] R_T \quad (19)$$

If the bracketed terms were constant, then the voltage-resistance relation would be linear. The presence of the R_T term in the denominator makes the coefficients vary with PRT resistance. In practice, the effect of variations in R_T can be minimized by building bridges with R large.

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For example, Figure 6.7 shows the voltage vs resistance for a bridge with R = 1000 ohms, R_s = 100 ohms, and E = 10 volts.

6.4 Instrumentation Linearity

Amplifiers are used to increase voltages, and transmitters are used to provide current signals in proportion to voltage signals. These operations would be error-free only if the operations performed were perfectly linear. Amplifiers and transmitters are adjusted by setting zero and span. Consequently, the errors at two points are determined by the uncertainties in the adjustments at those points, and the errors at other points are additionally affected by the instrument's nonlinearity.

6.5 Analog-to-Digital Conversion

Analog-to-digital conversion is required for systems which include digital readouts or computer processing of temperature signals. The uncertainty due to analog-to-digital conversion is:

$$\Delta T = 2^{-N} \text{ (SPAN) } B \qquad (20)$$

where

ΔT = temperature uncertainty,

N = number of bits in analog-to-digital conversion,

SPAN = span setting for temperature (°C), and

B = tolerance on analog-to-digital conversion (bits).

For example, the minimum uncertainty (B = 1) for a twelve bit analog-to-digital converter is 0.10°C for a 400°C span (wide range) and 0.01°C for a 50°C span (narrow range).

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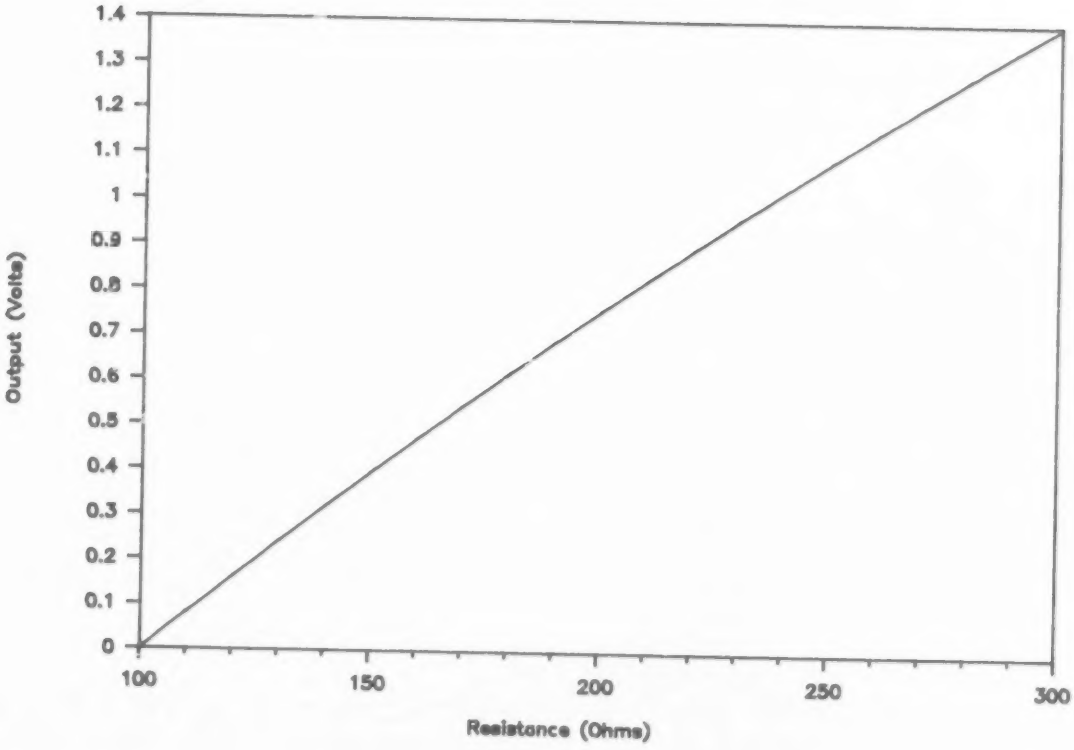

Figure 6.7. Voltage vs. resistance.

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6.6 Tuning

Adjustments of zero and span have been mentioned several times in previous sections. This standard procedure suffers additional deficiencies because a PRT is fundamentally a three-parameter instrument (R_0, α, and δ are needed to describe the sensor calibration). Consequently, a two-parameter adjustment only provides approximate matching of the instrumentation to the sensor. To use a two-parameter adjustment for a three-parameter device, only two approaches are possible:

1. Ignore the error (adjust the zero and span to minimize end-point errors or maximum error); or

2. Build the instrument with a fixed value for the third parameter (δ) which represents a typical value. The other two parameters (R_0 and α) are adjustable.

7. PRT DEGRADATION

In spite of the importance of measurement accuracy of PRTs, there have been very few reported experimental studies of PRT degradation. Tests on only a few hundred sensors provide the basis for assessing the performance of hundreds of thousands of PRTs used in industrial processes. Furthermore, many of the tests ran for only short time spans (days to weeks). Large errors have been observed (i.e. 25°C at 650°C), but it should be noted that errors for most of the sensors tested were much smaller (generally less than 0.05°C). However, it is important to know the maximum likely error in activities which require worst-case evaluation (accident analysis, replacement scheduling, calibration scheduling, etc.).

Tests have also been performed to assess another known error mechanism in PRTs, thermal hysteresis. Thermal hysteresis errors are those which occur as the PRT experiences temperature changes over some range. The hysteresis error is dependent on the path of varying temperatures experienced by the PRT. Errors as large as 0.3°C were observed.

The postulated physical basis for the known drift and hysteresis effects are summarized below. Ideally, experience and knowledge about PRT degradation would permit a quantitative assessment of drift rates under given operating conditions. Unfortunately, even the qualitative basis for PRT degradation is somewhat conjectural and quantitative predictions of the performance of a specific sensor is not possible. The following descriptions provide current conceptions of the mechanisms involved.

7.1 Strain

To achieve ruggedness, platinum wires or films in industrial PRTs are supported by attachment to an insulating structure over all or part of their lengths. The platinum and the insulator have different thermal expansion coefficients, so the platinum experiences stress when temperatures change. The resistance increases when the platinum is in tension and decreases when it is in compression. For small temperature changes, the stress is elastic, and consequently, reversible. This causes the PRT to have an altered value of α and makes the Callendar-van Dusen equation inappropriate as a fitting equation.

For large temperature changes, plastic deformations occur, and the effect is not reversible. The plastic deformation is essentially a work hardening effect which is characterized by an increase in internal energy of the metal. This internal energy can be relieved by annealing. At the annealing

temperature, the atoms in the lattice become more mobile and the internal energy drops to a stable condition. For platinum, annealing takes place at temperatures above 400°C. Hysteresis has been explained as the result of plastic deformation and friction between the sensor and its mounting which depends on the direction of relative motion between the metal and the mounting. For example, consider a wire attached to a mounting with a smaller thermal expansion coefficient than platinum. As the sensor cools, the wire shrinks more than the mounting and tensile stress occurs in the metal and plastic deformation occurs. When the sensor is heated again, the stress reverses and becomes compressive. However, the frictional resistance to motion is dependent on the direction of motion of the metal relative to the mounting. Therefore, the relief of the tensile stress has a different temperature dependence on heating than did the creation of the stress during cooling. Consequently, the R vs T behavior demonstrates hysteresis.

7.2 Oxidation

The formation of PtO_2 on the surface of platinum metal increases the resistance of the element at any temperature. Basically, surface oxidation replaces a fraction of the conductor's cross section with insulating material. In essence, the radius of the conductor is reduced by the thickness of the oxide. Oxidation effects have been observed to change the calibration of standards-grade PRTs up to 0.05°C. No studies of this effect have been published for industrial PRTs.

7.3 Contamination

One way to avoid oxidation is to build PRTs with reducing atmospheres inside the sheath. However, this leads to another degradation effect - metal ion migration. At temperatures above 500°C, metal ions migrate from the metal sheath to the platinum where they interact metallurgically and cause a shift in R_0, and a lowering of α. Changes of R_0 of as large as 0.5% have been reported. This gives an ice point measurement error of 1.3°C.

7.4 Quenching

Annealing at temperatures above 400°C is commonly used to eliminate strain effects in PRTs. However, proper annealing requires slow cooling. Rapid cooling causes quenched-in lattice defects. These defects shift R_0 and reduce α.

7.5 Grain Growth

The performance of a PRT depends on the condition of the crystal lattice of the metal. Grain growth occurs in platinum at temperatures above about 420°C after long durations of exposure at these temperatures. When metals are heated after plastic deformation, grain growth occurs. The grain boundaries are weak points in the wire and shock or vibration can cause grain boundary sliding. This increases the electrical resistance of the wire and affects the sensor's calibration.

7.6 Cold Working

Mechanical shock and vibration can cause cold working of metals. This work hardening effect alters the lattice structure of the metal and affects its R vs T performance. Cold working can be removed by annealing.

7.7 Insulation Break Down

The electrical shunting problem due to inadequate insulation resistance was discussed in Section 5.3. Insulation resistance changes due to moisture can change during sensor life, so insulation resistance change is a possible degradation mechanism. If the seal at the head of the sensor is imperfect, or if cracks or holes exist along the sensor sheath, then water can enter or leave the PRT. Operation of a PRT for extended time at elevated temperatures gives two opposing effects:

1. Seals dry out, shrink, crack, and leak;

2. The higher temperature inside the PRT causes the water vapor to diffuse out of the sensor.

In general, the effect of moisture on insulation resistance is a concern in PRT operation. Fortunately, a resistance measurement between one of the PRT leads and ground can be used to check for this problem. The resistance is measured with an instrument which applies 50 to 100 vdc across the PRT. The test duration must be sufficient to allow polarization of the water to saturate.

8. BURN-IN OF PRTs

Typically, PRTs are built and calibrated long before installation in a plant. The elapsed time may be as long as years. In principle, the sensors are treated carefully and no shock or vibration effects are induced. Furthermore, it is usually assumed that the sensor manufacturer has done a good job of annealing and minimizing design-related strain effects. These assumptions may be valid, but because of the importance of accurate temperature measurement in nuclear power plants, it may be prudent to implement a simple burn-in test to check the pre-installation condition of the PRTs. A possible burn-in program is:

1. Check calibration. A four-point check should be performed (at approximately 0°C, 100°C, 200°C, and 300°C). The four-point calibration will permit assessment of the conformity of the R vs T relation to the Callendar-van Dusen equation. Departure from conformity is a clue that platinum strain or chemical contamination is present. Also, the calibration should involve seven measurements (0°C, 100°C, 200°C, 300°C, 200°C, 100°C, and 0°C). This would reveal strain-induced hysteresis.

2. Anneal. Bring the PRT to 450°C for 24 hours, then cool slowly.

3. Repeat the calibration as in Step 1. This will show whether the PRT is susceptible to strain or whether the sensor originally had quenched-in or grain growth defects.

4. Install in a furnace at 300°C for two weeks.

5. Repeat the calibration as in Step 1. The two-week duration was selected as a reasonable period to look for long-term problems such as insulation break down.

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9. PRT CHECKING, RECOVERY, AND RECALIBRATION

After installation in a plant, the concern about decalibration begins. It is inappropriate to assume that PRTs automatically give accurate measurements after extended use. PRTs are generally excellent sensors, but they are not infallible. The in-plant checking involves the following:

1. Cross checking. Redundant sensors are used in nuclear plants. Limited information on sensor drift is available through comparison of sensor readings. However, for identical sensors, there is always the possibility of common mode degradation. Ideally, multiple sensors based on diverse measurement principles (PRTs and thermocouples) should be available. If this is not done, the next best option is multiple PRTs from different manufacturers. This guards against design-related or manufacturing-related common mode problems.

2. Insulation resistance. The insulation resistance is easily measured. The measurement error can be estimated using Equation 15. When the estimated error reaches some level (i.e. 0.1°C), the sensor should be replaced.

3. Thermoelectric effect. While errors due to thermoelectric voltages are not due to degradation of the PRT, it is a worrisome effect which is susceptible to simple testing. Thermoelectric effects cause changes in the indicated temperature when leads to the transmitters are reversed. The lead-reversal test should be performed periodically (i.e. quarterly), and the PRT should be replaced or the wiring should be corrected if the error is greater than a given tolerance (e.g. 0.1°C).

The only established way to check PRT accuracy is to remove and calibrate them. In-situ calibration methods are under development, but they have not yet been qualified for field applications. Some of the PRTs should be removed and calibrated every shutdown. The remaining PRTs can be evaluated by cross checking against the recently-calibrated PRTs.

If a PRT is found to have decalibrated, it may still be possible to use it again in the plant. This is desirable because of the high cost of PRTs for nuclear plant safety systems. If the calibration is restored by annealing at 450°C, then the PRT may generally be considered "as good as new."

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10. SUMMARY OF FINDINGS AND RECOMMENDATIONS

Errors in temperature measurements with platinum resistance thermometers used in nuclear power plants are likely to be comparable to, or greater than tolerances currently required (as small as 0.1°C). This is true at initial sensor installation, and the concern increases with time in operation.

The actions recommended as a result of this investigation are:

1. Re-examine tolerances on temperature measurements. Some are extremely tight and probably do not reflect real needs or real capabilities of modern temperature sensors.

2. Initiate a burn-in program for new sensors.

3. Initiate a program of routine, simple tests to check for sensor problems.

4. Initiate a program of scheduled sensor removal and recalibration.

5. Develop a better data base of information about degradation mechanisms, their magnitudes, and their rates. This will involve theoretical work, single effects experiments, and long-term testing of typical PRTs.

6. Initiate a policy of avoiding a single sensor design in making redundant measurements.

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13. ABSTRACT (200 words or less)

A program was established and initial tests were performed to evaluate long term performance of resistance temperature detectors (RTDs) of the type used in U.S. nuclear power plants. The effort addressed the effect of aging on RTD calibration accuracy and response time. This Phase I effort included exposure of thirteen nuclear safety system grade RTD elements to simulated LWR temperatures. Full calibrations were performed initially and monthly, sensors were monitored and cross checked continuously during exposure, and response time tests were performed before and after exposure. Short term calibration drifts of as much as 1.8°F (1°C) were observed. Response times were essentially unaffected by this testing.

This program shows that there is a sound reason for concern about the accuracy of temperature measurements in nuclear power plants. These limited tests should be expanded in a Phase II program to involve more sensors and longer exposures to simulated LWR conditions in order to obtain statistically significant data. This data is needed to establish meaningful testing or replacement intervals for safety system RTDs. An important corollary benefit from this expanded program will be a better definition of achievable accuracies in RTD calibration.

This report concludes a six-month Phase I project performed for the Nuclear Regulatory Commission under the SBIR program.

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